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The Environmental and Pollution Aspects of Coal Slurry Pipelines

Colorado School of Mines, Golden

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THE ENVIRONMENTAL AND POLLUTION ASPECTS
OF COAL SLURRY PIPELINES

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report contains an assessment of the environmental and pollution aspects of coal slurry pipelines. This study was conducted to supply information to EPA on the environmental impacts associated with the design, construction and operation of a coal slurry pipeline. Further information on this subject may be obtained from the Extraction Technology Branch, Resource Extraction and Handling Division.

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ABSTRACT

With the anticipated increases in coal consumption in the next decade, greater demands will be made on existing transportation systems to move to market the abundant reserves of coal in the United States. Conventional transportation modes such as rail and barge will have to expand their capabilities by overcoming those shortages that may exist in labor, capital, and equipment. Simultaneously, lesser known systems such as coal in water (slurry) pipelines will have to share the transportation load.

The environmental impact of a coal slurry pipeline system may occur during design, construction, or operation and maintenance; and it may involve any of three areas--slurry preparation, transportation, and separation. The evidence suggests that the environmental and pollution aspects of coal slurry pipelines as a system are less than alternative transportation modes. Methods are suggested to enhance the selection of better design, construction, and operation techniques to provide a balance of engineering, economic, and environmental considerations.

The major expansion of coal production is expected to take place in the West, where, traditionally, water has held top priority. The exportation of water as a liquid carrier for coal will provoke many political, legal, and economic confrontations. The water issue, although predominant, cannot be fully addressed because of unknown long-term effects of water withdrawal from deep groundwater sources.

A possible solution may be the advent of energy slurries consisting of hydrocarbon solids and liquids that require less water in their processing, take advantage of economical pipeline transportation, and eliminate costly dewatering circuits. The environmental and pollution aspects of energy slurry pipelines are expected to be similar to those of oil pipelines.

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SECTION 1

INTRODUCTION

Expansion and diversification of environmentally acceptable U.S. energy sources have been widely called for by the media. This call has been created by these circumstances:

1. the depletion of low-cost domestic oil and gas resources,
2. the high cost and heavy dependence on foreign oil and gas supplies, and
3. the present unreliability of nuclear systems.

These factors have produced a sharply increased interest in returning to coal, since coal is the most plentiful source of energy in the United States. In fact, we have nearly half of the world's reserves of coal. Coal-bearing rocks, which are present in 37 states, underlie some 13 percent of U.S. land.

U.S. coal resources, as estimated by the U.S. Geological Survey (1), are much larger than our resources of oil and gas combined. With these coal resources, the United States can provide many decades of fuel and hydrocarbon supplies to meet future energy demands. The technologies for mining, washing, transporting, and burning of coal are well known. Coal can be converted into electricity, heat, and gas and, in the future, into heavy liquids and light distillates to serve almost all the energy-consuming markets.

In the United States, coal production faces some environmental problems that in turn affect the cost and the availability of coal. These environmental constraints are the following:

1. Land impacts: Land is altered by the method of mining used e.g., surface mining depresses the topography.
2. Human resource impacts: There are health and safety risks in surface and underground mining.
3. Air impacts: Air pollution is created by combustion by-products such as fly ash and bottom ash.

According to the National Coal Association (2) U.S. coal production will set a record high of 704 million tons in 1977, a 5.8% increase over 1976 production (Table 1). These records are finally surpassing the postwar boom year of 1947, when the U.S. produced 631 million tons.

Table 1 shows U.S. coal production and consumption by mar-

TABLE 1. UNITED STATES PRODUCTION AND CONSUMPTION
OF BITUMINOUS COAL 1947 --1977 *
(Thousands of Tons)

Year	Elect. pow. utilities	Rail- roads	Coking coal	Steel & roll- ing mills	Cement & mfg.	Retail de- liveries	Total U.S. consumption	Total U.S. production
1947	86,009	109,296	104,800	14,195	134,934	96,657	557,243	630,624
1952	103,309	37,962	97,614	9,632	103,379	66,861	418,757	466,841
1957	157,398	8,401	108,020	6,938	97,199	35,712	413,668	492,709
1962	190,833	x ⁺	74,262	7,319	87,182	28,188	387,774	422,149
1967	271,784	x	92,272	6,330	92,931	17,099	480,416	552,626
1970	318,921	x	96,009	5,410	83,207	12,072	515,619	602,932
1971	326,280	x	82,809	5,560	68,862	11,351	494,862	552,192
1972	348,612	x	87,272	4,850	67,131	8,748	516,776	595,386
1973	386,879	x	93,634	6,356	60,837	8,200	556,022	591,738
1974	390,068	x	89,747	6,155	57,819	8,840	552,709	601,000
1975	403,249	x	83,272	2,715	59,759	7,282	556,301	640,000
1976	442,000 (est)	x	85,000	NA	NA	NA	597,000	665,000
1977	NA [†]	x	NA	NA	NA	NA	NA	704,000

* Source: U.S. Bureau of Mines (4)

⁺ x - discontinued.

[†] NA - Not available.

kets for selected years. Coal consumption in the United States has declined almost 200 million tons between 1947 and 1958. The comeback of coal in the 1960's was largely produced by development in the electric utility fuel market, the coal industry's only growing market.

In the early part of the century, coal supplied almost 80 percent of the nation's energy (Table 2). Shortly after World War II coal provided less than 40% of our nation's energy when railroads shifted from coal-fired steam locomotives to diesel engines to avoid the problem of coal handling. At the same time, home coal furnaces shifted to cleaner, more convenient, and environmentally acceptable sources of energy--oil and natural gas.

Western coal is expected to supply most of the increase in U.S. coal production. For example, the Powder River Basin of Wyoming is projected to produce 86 million tons per year by 1985 from a total of 21 mines. In 1975 there were only 5 active mines there (3). Colorado produces about 7 million tons per year from fewer than 40 mines.

Major breakthroughs in technology will play a large role in the future domestic markets of coal. Coal for the synthetic fuel markets will be used in the early 1980's for the production of synthetic pipeline gas, synthetic liquid fuels, and sulfur-free clean coal for use in power utility plants, refineries, or other industries.

Today there are many processes for synthetic fuel production from coal. Some are at the laboratory bench scale stage, some are at the pilot plant stage, and some are at the production stage.

The National Academy of Engineering (6) estimated that coal production in the United States by 1985 will be double the current annual output of 670 million tons. Consumption was also forecast and is shown on the next page.

TABLE 2. ENERGY SUPPLIES IN THE U.S.*

Source of Energy	1920	1950	1973
Coal	78%	38%	18%
Petroleum	14	39	46
Natural gas	4	18	31
Hydro	4	5	4
Nuclear	-	-	1
Total	100%	100%	100%

*Source: Ford Foundation (5)

<u>Fuel:</u>	<u>1985 consumption million tons/year</u>
Coal solids (for utilities, industries, and residences)	950
Synthetics.	310
Total	1,260

From these figures, it is anticipated that the synthetic fuel industry will be consuming about 25% of the total production.

COAL TRANSPORTATION

Since coal is a source of energy, it must be transported to the vicinity of use in one form or another either in its natural state, as electricity, or as a refined product, as a gas or a liquid. Currently the economics of coal utilization, particularly as an energy source for electric power generation, favor moving it and using it in its natural state (6).

In the United States there are four major modes of transporting coal to markets in its natural form: railroads, barges, trucks, and miscellaneous--including tramway, conveyors, slurry pipelines (Table 3).

The western states are expected to play an important part as the United States approaches "Project Independence." Some experts predict that annual consumption of western coal from Wyoming, Colorado, and neighboring states will rise from 21 million tons in 1971 to 362 million tons in 1980 (7). Because of the remoteness of western coal fields, and the low population density of the western states, increased coal production will necessitate movement to market by all of the existing transportation modes. The railroads certainly cannot handle all of the in-

TABLE 3. COAL TRANSPORTATION MODES IN THE U.S. IN 1973*

<u>Mode</u>	<u>Percent</u>
Railroads	52
Barges	27
Trucks	12
Miscellaneous: (tramway, conveyor, and private railroads)	8
Slurry Pipelines	1
Total	100

*Source: U.S. Bureau of Mines (4)

crease. Waterways are cheapest but limited geographically. Moreover, there are no waterways in the West within a hundred miles of the coal fields. Trucks are not economical for long distance and large volumes. Therefore, slurry pipelines must play an increasingly important role in transporting coal where water is available. Alternate transportation modes are discussed in more detail in the next chapter.

Chemical Engineering (7) shows Steffes' projection that railroads and slurry pipelines will transport almost equivalent amounts of western coal by 1980, as shown, in the following:

<u>Million of tons per year</u>	
Moved by rail for utilities and industry	165
Moved by slurry pipelines for utilities and industry	162
On site generation station (EHV)	20
Substitute Natural Gas (SNG) from coal.	15
Total.	362

This anticipated growth in use of coal slurry pipelines provides the impetus for this study, which involves a closer look at coal slurry technology, in particular its environmental and pollution aspects. Technology will be examined first.

State of the Art

In a coal slurry pipeline, coal is mixed with about an equal weight of water and pumped through a pipe. The coal and water together are referred to as a two-phase (solids-liquid) system or slurry. Pumping a two-phase system such as a coal slurry is much more complex than pumping a single-phase such as water. The mathematics describing the behavior of water under certain conditions is very well established and has been so for more than a century. Also, basic water properties do not vary significantly from place to place. (The comparison of fresh water with sea water is a possible exception.)

While water properties are fairly constant, coal properties vary according to source and sometimes even within the same coal seam. Coal properties in place include specific gravity, rank, moisture content, ash content, volatiles, sulfur content, and hardness. Additional properties observed once the coal is mined are size and shape of coal particles, surface texture, amount of entrapped methane, and size distribution. Size distribution describes the size range of coal particles--whether they are one size or if there are varying amounts of powdery or lumpy particles generated when the coal is mined or crushed. Size distribution is expressed as a percent passing through or retained on sieves of different standardized hole sizes.

Once the coal is mixed with water additional properties of the slurry can be varied. The concentration of the coal present in the water is an important variable, particularly since it represents the payload of the pipeline system. Other variables include the temperature and viscosity of the slurry. Viscosity is a property measuring the fluidity of the slurry.

With the high variability of coal properties, it is easily concluded that no two coal slurries are exactly alike, and this is what has generally been observed. Though different coals will have similarities within certain limits when mixed with water and pumped in a slurry, no two slurries will behave identically when pumped through identical systems. Each slurry has its own unique hydraulic characteristics.

Coal Slurry Preparation, Transportation, and Separation

In the preparation stage coal is pulverized to a specified size and is usually mixed with an equal amount by weight of water. The resulting slurry is pumped at about 1-1/2 to 2 meters per second through a pipeline that is usually underground. Over long distances the necessary flow is maintained by intermediate booster pump stations. At its destination the coal is removed from the water by means of centrifuges, vacuum filters or thermal drying as required. Since the coal is saturated with water, the two phases are not always easy to separate. The coal is used as boiler fuel to generate electricity, and the clarified water is beneficially consumed as a small part (about one-eighth) of the power plant cooling requirement (8,9,10).

Pipelining solids in slurry form is now supported by substantial technology and is backed by the experience gained in many commercial installations. Many materials can be slurried and pumped through a pipeline, and their hydraulic behavior can be fairly well predicted by the use of laboratory tests and computer models so that a reliable design can be made. Designs must be tested in loop systems when scaling to larger diameter pipes is required. Technology of slurry pipelining is well developed and so is the art of applying it. Though improvements are desirable, the necessary equipment is commercially available and adequate.

Coal slurry hydraulics relate the many variables which must be managed in order to attain a stable slurry. This stability refers to maintaining flow velocities low enough to keep power requirements moderate and abrasion negligible yet high enough to prevent deposition. Bedding can lead to pipeline plugging. However, most slurry systems are designed to minimize the chance of plugs even in a rapid, unplanned shutdown such as a power outage. Experience has shown that a slurry pipeline filled with a properly constituted slurry can be shut down and then restarted up to four days later without difficulty (11). Restart time to full

operation and slurry homogeneity was 2 to 3 minutes for the Ohio pipeline (12).

To transport solids successfully in slurry form, enough energy in the form of turbulence must be imparted to the slurry to keep the solids in suspension. It is important to have some powder-fine material in the slurry to provide the viscosity which supports the coarser particles at lower velocities. Nevertheless, the operating velocity in the pipeline must be high enough to provide the necessary turbulence. If the velocity is not maintained at this level, the coarser particles will tend to move toward the bottom of the pipe, causing localized wear and increased risk of plugging. Conversely, at high velocities, wear and excessive pumping horsepower can also be problems. Hence, a slurry pipeline may be considered as having speed limits, both minimum and maximum.

The speed limit aspect of slurry pipelines is one reason for their complexity. It is a design constraint around which other design parameters revolve. Pipe diameter determination is an example of the complex interrelationships of system variables. As pipe diameter increases, the capital cost of the line increases almost parabolically because the cost is a function of the weight of steel in the pipe (13). At the same time operating costs (per ton of coal delivered) drop because friction losses are lower in larger pipe. Combining the capital cost and operating cost curves usually yields a horseshoe-shaped curve with a minimum total cost related to a certain diameter. But this is cost at a fixed annual throughput capacity. When the speed limit concept is added to the economic examination, the "point" answer of minimum cost becomes an "area" answer in which one of several points must be eventually selected. Sometimes because of unique slurry properties the system must be operated at a higher level than the hydraulic minimum to make it more cost effective (Figure 1).

Even though the design method is unique and complex, from all outward appearances the slurry pipeline itself is virtually identical to an oil or gas line. This pipe is conventional line pipe coated to provide for external corrosion protection. Internal coating has not been attempted commercially for slurry pipelines but is being considered. The coal absorbs some oxygen reducing internal corrosion, but sometimes a corrosion inhibitor must be added to minimize this problem. The mechanism of corrosion also can be found in conventional water pipelines as a coating of oxidized material (rust scale) on the inside of the pipe. The addition of solids causes this coating to be eroded away as soon as it forms in a corrosion/erosion synergistic effect which accelerates internal wear. A small additional pipe wall thickness is included in the design to provide for this problem. Wall thicknesses generally range between 0.5 cm and 1.25 cm.

Every transportation system has its limitation. In addition

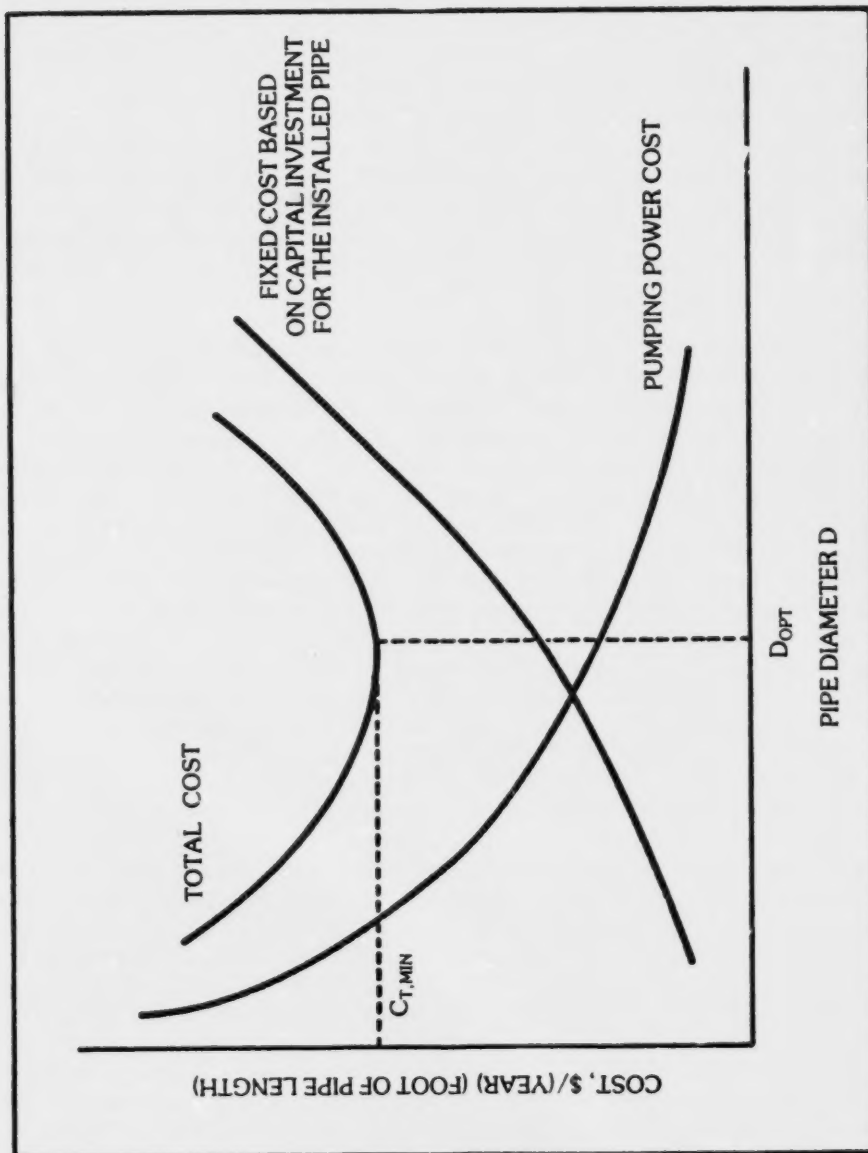


Figure 1. Optimum pipe diameter for a minimum total cost at a fixed mass flow rate. (14)

to the speed limit problem for pipeline operation, there is the difficulty in slowing the flowrate when process requirements at the terminal end of the slurry pipeline are low. An example of this would be the reduced load of a power plant that has a turbine-generator malfunction or a related problem. A coal slurry pipeline handles this problem by maintaining constant communication with the power plant it feeds and can plan pumping with the aid of a computer prediction model. Throughput can be reduced by decreasing the concentration of coal, maintaining the design concentration but interspersing it with slugs of water (batching), or shutting down the pipeline. Another limitation may be allowable moisture content of the delivered coal. If the ultimate process requires the use of dry material, then dewatering the slurry and clarifying the water becomes an important consideration and one that may be difficult and costly.

Past, Present, and Planned Pipelines

Slurry pipelines carry literally everything from A to Z-- from aluminum oxide to zinc oxide. Appendix A is a partial listing of the larger slurry pipelines known to the author. The vast majority of slurry pipelines emanate from the minerals industry. Just a few originate from the agricultural and other non-minerals industry. Most of the solids-carrying pipelines transport mineral tailings. Thus waste disposal is the prime use for slurry pipelines. Slurry pipelines also transport mineral concentrates or beneficiated ores, as well as raw ores.

The first recorded slurry pipeline appears to be one used in gold placer operations in California in the late 1850's (15). (A detailed history of slurry pipelines is given in the same reference.) Coal pipelines were mentioned in a patent application by W.T. Donnelly of Brooklyn, N.Y., in 1904. In England, G.G. Bell built a 200 mm diameter pipeline over 600 m long for unloading barge coal hydraulically. In 1957 the Russians claimed in Ugol that they had built the first long distance coal pipeline--300 mm diameter, 61 km long, transporting 220 tph at 1.5 m/s (15).

The evolution of coal slurry pipelines in the United States began in 1957 when a 250 mm diameter pipeline, 173 km in length, was operated for six years, delivering coal in slurry form from Cadiz to the East Lake Generating Station near Cleveland, Ohio. Rail tariffs had climbed to \$3.47 per ton. The pipeline delivered coal at less than \$3.00 per ton, which included preparation and dewatering costs. After six years the railroad succumbed and lowered its tariff to \$1.88/ton (16). The pipeline was then mothballed but kept on call as a lever against the railroad.

In November 1970 the Black Mesa pipeline came on stream and is still operating. The transportation cost was stated as \$2.50 per ton in 1975 and \$3.00 per ton in 1976 (9,17). Though 3.765 million tons of coal were transported in 1975 compared to 4.2

million tons of coal in 1976, the increase in unit transportation cost was due primarily to increased power costs. This pipeline was built where no continuous trackage existed over the entire route. Where a few rail crossings were necessary, these were negotiated by the Black Mesa Pipeline Co. and the individual railroad effected.

Continuing interest in the mid-seventies shows nearly a half dozen coal slurry pipelines in the wings, much larger and longer than their predecessors (Table 4)(18). The third slurry pipeline system, Allen-Warner for Nevada Power Co., is expected to begin service in 1983 (19). In this case, sufficient rail trackage does not exist and the topography is too rugged for a unit train. The pipeline system will consist of two parallel pipelines, each feeding a separate power station. A common preparation plant at the Alton coal field near Kanab, Utah, will feed the Warner Valley power station near St. George, Utah; by 109 km of 300 mm diameter pipe and 8 km of 200 mm diameter pipe carrying 2.27 million tonnes* of coal annually. The second pipeline, consisting of 262 km of 550 mm diameter pipe and 30 km of 500 mm diameter pipe, will carry 8.26 million tonnes of coal annually to the Allen power station near Las Vegas. Both pipelines utilize short distances of small diameter pipe to dissipate energy through increased pipewall friction over excessively steep terrain.

Before the design of the Allen-Warner pipeline, Energy Transportation Systems, Inc. (ETSI) proposed a 1661 km pipeline from Gillette, Wyoming, to utilities near Little Rock, Arkansas. Almost 50 rail crossings would be required and this is where the confrontation began. The railroads denied access, thus forcing the quest for eminent domain by the Slurry Transportation Association, a lobby newly formed for this purpose.

In 1976 Houston Natural Gas and the Denver and Rio Grande Western Railroad informed the State of Colorado of a proposed coal slurry pipeline system (San Marco)(Figure 2). Nine million tonnes of coal annually would be moved by rail from several Colorado mines to Walsenburg, Colorado. Another 4.5 million tonnes would arrive from Farmington, New Mexico, by slurry pipeline. A water field in the San Luis Valley of Colorado would supply water to the Farmington slurry preparation plant and to the Walsenburg slurry preparation plant. Annual water requirements are estimated at $12.34 \times 10^6 \text{ m}^3$ (10,000 acre-feet). The combined 13.5 million annual tonnes of coal would be slurried and pumped to Texas with intermediate annual deliveries of 1.1 million tonnes to Amarillo, a similar amount to a utility 112 km south west of Amarillo, and 4.5 million tonnes to Temple. The remaining 6.8 million tonnes would continue on to Angleton, south of Houston. Operation was to have begun at the end of 1979, but the securing of water supplies in Colorado has been delayed by legal and po-

*Ton=short ton; tonne=metric ton

TABLE 4. COAL SLURRY PIPELINES IN THE U.S.

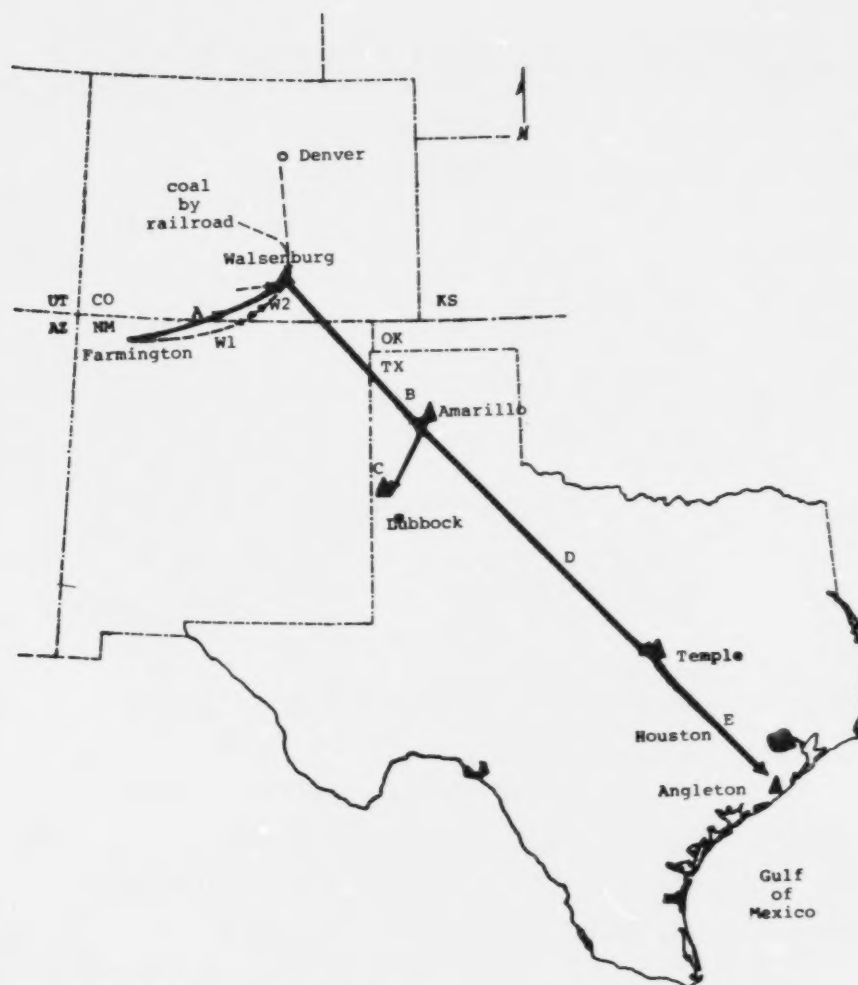
<u>Existing Lines</u>				
Name	Origin/terminal	Length (km)	Diameter (mm)	Capacity (million tonnes/An.)
Consolidation*	Cadiz, Ohio to Cleveland, Ohio	173	254	1.2
Black Mesa	Kayenta, Ariz. to Nevada	436	457	4.4
<u>Planned Lines</u>				
ETSI ⁺	Gillette, Wyo. to White Bluff, Arkansas	1661	965	23
Houston Nat. Gas	Walsenburg, Colo. to Houston, Texas	1864	203-711	13.6
Salt River ‡	Star Lake, N.M. to St. Johns, Ariz.	288	406	-
Nevada Power	Alton, Utah to Arrow Canyon, Nev.	412	200-550	10.5
Gulf Inter- state	Gillette, Wyo. to Boardman, Oregon	1280	762	14.5
Montana/ Houston	Southern Montana to Houston, Texas	2024 [#]	1016	26

* Is not in operation at this time.

+ Energy Transportation Systems Inc.

‡ Cancelled.

Estimated from the map (20).



Line	Length km	Size mm	Capacity MMTPY
A	355	406	4.5
B	466	711	13.5
C	107	200	1.1
D	624	660	11.1
E	312	508	6.8
W1	88	508	10,000
W2	267	305	Ac.-ft.

Figure 2. Proposed Colorado-Texas (San Marco) coal pipelines.

litical complications.

The existence of so many slurry pipelines attests to their proven technology. However, the advent of the coal-water slurry pipeline on the domestic scene has raised questions of eminent domain, water usage, and environmental impact. Before examining the latter two questions in detail, a comparison of other modes of transporting coal will be made.

SECTION 2

ALTERNATE ENERGY TRANSPORTATION MODES

COAL TRANSPORTATION

Though the United States is currently researching alternate energy sources such as the fast breeder reactor, fusion, geothermal energy, wind power, and solar power, none of these can be considered short-term solutions to the energy shortage (21). They may be considered long-term solutions, however, while coal-derived synthetic fuels may be regarded as intermediate solutions. The short-term solution, it appears, will have to be coal.

One problem surrounding domestic energy production is the selection of the optimum method of transporting the energy from the producer to the consumer. Coal transportation trends have changed and will change in future years (Table 5).

Pipelines will probably see additional growth as gasification and liquifaction plants are built to produce synthetic fuels from coal. Evidence is yet too sparse to conclude whether it is more advantageous economically and environmentally to transport coal to the area of consumption or to convert the coal to synthetic fuels at the mine and pipeline them to the area of energy consumption. Presently, pipelines move one-fourth of all the freight tonnage, primarily oil, petroleum products, and natural gas (23).

TABLE 5. COAL TRANSPORTATION*
(Average Percent)

Period	Rail	Barge	Truck	Slurry pipeline
'37-'40	83.7	5.5	7.8	-
'48-'51	81.5	5.1	10.4	-
'70-'73	66.8	11.4	11.0	0.4
1985(est.)	52	16	10	8

*Source: J.W. Scales (22)

Pipeline Safety

Safety has always been one of the major advantages of pipelines. A Summary of Accidents Related to Non-Nuclear Energy, (24) a U.S. Environmental Protection Agency Publication, examines the safety of pipelines as follows (24):

a) Coal:

Transportation accidents account for 10-15% of mining fatalities. In underground mining operations, hauling is the most dangerous function. Although such accidents are not frequent, they are severe. Coal is transported to the consumer via rail, trucks, and slurry pipelines. These three rank from most to least dangerous in terms of fatal injuries per 10¹² BTU* equivalent tons shipped as follows: railroads are most dangerous at 0.06 followed by trucks at 0.032 and slurry pipeline at 0.0019.

b) Crude Oil:

Transportation of oil via tankers accounts for a greater number of fatalities and injuries annually than transportation of oil via pipeline. Pipeline accidents number approximately 135 per year, and cause approximately one fatality and one injury per year. Tanker accidents number approximately 640 per year and cause approximately 75 fatalities and 35 injuries per year.

c) Natural Gas and Liquified Natural Gas (LNG)

Almost all pipeline accidents can be attributed to corrosion, damage by outside forces, construction defects, or material failure. The Eighth Annual Report of Pipeline Safety summarized gas pipeline accidents during 1975. [See Tables 6 and 7] With a total of 1,373 failures this amounts to 0.01 fatality per failure and 0.17 injury per failure. Pipeline transportation poses a significant hazard to the general public [only] when pipelines transect residential and commercial areas.

According to statistics tabulated by the U.S. Department of Transportation (25,26), most gas pipeline accidents (54% to 58%) are the result of damage from outside sources. During the same period (1972 and 1973), construction defects or material failures accounted for 19.5% to 23.5% of the total failures. Table 8 sum-

*This amount of energy is equal to that required to run a 1000 MW power plant for approximately 300 hrs, or to that needed to heat approximately 5000 homes for one season (October through April) in a temperate climate.

TABLE 6. NATURAL GAS ACCIDENT DATA*

Technology	Fatalities /10 ¹² BTU	Injuries /10 ¹² BTU	Fatalities /year	Injuries /year
Pipeline distribution	0.000040	0.0138	8	220
Extraction offshore	0.000007	0.0030	-	-
onshore	0.000080	0.0040	16	-
Transmission & gathering	0.000006	0.0010	6	17
Processing natural gas				
liquid	0.000040	0.0040	3	921
hydrogen sulfide	0.000002	0.0020	-	-

*Source: Reference 24

TABLE 7. PIPELINE ACCIDENT DATA - 1975*

Mode	Non-employee injuries	Non-employee fatalities	Employee injuries	Employee fatalities
Distribution	191	8	29	0
Transmission & gathering	<u>9</u>	<u>1</u>	<u>8</u>	<u>5</u>
Total	200	9	37	5

*Source: Reference 24

TABLE 8. GAS PIPELINE ACCIDENTS, 1972-73*

Accident cause	Total no.	Fatalities		Injuries	
		Employ	Non-employ	Employ	Non-employ
1972:					
Corrosion	74	0	0	0	0
Damage by outside forces	219	0	0	8	4
Construction defect or ma- terial failure	80	0	2	4	1
Other causes	<u>36</u>	<u>3</u>	<u>1</u>	<u>11</u>	<u>8</u>
Total	409	3	3	23	13
1973:					
Corrosion	63	0	0	1	0
Damage by outside forces	272	0	0	0	15
Construction defect or ma- terial failure	111	0	0	0	0
Other causes	<u>25</u>	<u>1</u>	<u>1</u>	<u>2</u>	<u>1</u>
Total	471	1	1	3	16

*Source: References 25,26

marizes accident statistics for the transmission of natural gas in 1972 and 1973.

Unit Trains

A unit train is basically a long train (almost 2 km) pulling cars filled with one commodity that is going from one location to another with no intermediate stops. In the case of unit trains carrying coal the train is generally 90 to 110 cars in length, each car containing about 90 tonnes traveling between a mine and a consuming facility, usually an electric generating plant.

Two thirds of all the coal produced in this country now is carried by rail. This traffic in coal brought the railroads \$2.1 billion in revenue in 1975--a 50% increase over the 1973 figure. Of the 400 million tons of coal carried by the railroads in 1975, half was in unit trains. Coal accounted for 30% of all tonnage in railroad freight in 1976 and contributed 13% to total railroad revenues (27). According to Scales (22), this trend will continue with the advent of increased coal production in the West despite competition from coal slurry pipelines, mine-mouth power plants, and gasification and liquefaction plants.

Unit trains have proved to be a competitive mode of transporting materials since their inception in 1963 when a unit train tariff undercut the costs of the first U.S. coal slurry pipeline in Ohio. As their use has increased, the hopper car manufacturers have gone from rotary-dump cars to bottom-dump cars with steeper door chutes that allow full-car unloading in a few seconds. Maintenance costs on unit train hopper cars are estimated at about 1.7¢/tonne-km. Their life expectancy is not well documented because of basic changes in design (28).

It can be assumed that improvements in railroad technology will continue, but one example of a step forward in train technology failed recently in Arizona (29). It was discovered that concrete ties would not hold up to over-sized unit train operation and eventually failed. A 110-tonne car was used as opposed to the normal 90-tonne car. Automation of the unit train was also attempted. Because of an excessive number of flaws, the automation system was disconnected and the unit train is now operated manually. Similar systems had worked well in other locations but not on this larger scale.

Unit trains will be carrying most of the coal in the decades ahead. The clear-cut advantages of unit trains can be summarized briefly. In comparison to most other transportation modes, trains need little water to operate, a factor especially important in the western states. This is assuming that all locomotives are diesel-electric and consume diesel fuel. If another oil embargo of long-term duration occurs, making diesel fuel scarce, coal-fired boilers could be used to power locomotives and water

then would be required. This possibility is extremely remote.

Another advantage is that most of the track for unit train haulage to electric utilities already exists, and the cost of the trackage has been mostly absorbed by the railroads. Whether this trackage is capable of handling intense unit train use is a question that will be subsequently addressed. In addition, railroads are relatively flexible and can expand or cut back service easily with demand variations. It remains to be seen how extreme an expansion can be handled by the nation's railroads.

The general assertions that trains are fast, dependable, and energy conserving are somewhat difficult to substantiate. [Unit trains move at 30 to 50 km/hr under load and nearly double these speeds on the return empty haul.] Wasp (30) has provided some data for a comparison of unit trains with slurry pipelines (Table 9).

Railroads also have the advantage of offering more permanent jobs than other modes, specifically pipelines and EHV lines from mine-mouth power plants. This is a specious argument, however, in light of most attempts by industry to reduce high labor costs through automation.

The relative disadvantages of the use of railroads to transport coal can also be briefly summarized. According to Wasp (30), railroads have higher capital costs than slurry pipelines--as much as 50% higher when original trackage does not exist. This is due partially to railroad grade restrictions requiring 30% extra distance more than that necessary for a slurry pipeline. New railroad construction costs vary from \$500,000 to over \$1,000,000 per mile, depending basically on the severity of the terrain crossed (31).

Furthermore, railroad tariffs have a traditional sensitivity to inflation--rail tariffs have increased at almost double the rate of the national inflation rate. A recent statement from the Council on Wage and Price Stability shows that with the latest 1977 rate increase of 5%, rail freight rates have escalated 106.7% since 1970. During the same period the implicit price deflator for total GNP increased by 55% and the consumer price index rose 56% (33). Historically, a tariff escalation rate of 3% for railroads has been predicted (22), but in the year 1975-76 statistics published by the U.S. Bureau of Mines show an increase of about 9.5% (34).. This is related to the high labor requirements of operating a railroad. In addition, the increased coal traffic in the West may cause severe wear problems and deterioration of grade ballast under increased traffic.

Some utility executives have spoken recently in favor of coal slurry pipelines. Mr. F. Lewis, president of Middle South Utilities, has stated, "Expressed in dollars, the annual movement of

TABLE 9. COMPARISON OF REQUIREMENTS FOR 22.7×10^6 TONNES
ANNUAL COAL HAUL FROM WYOMING-ARKANSAS*

Item	Slurry pipeline	Unit train
Distance, km	1670	2201
Estimated life	30 yr	30 yr
Capital cost($\$10^6$)	750	730 ⁺
No. of unit trains	-	46
Locos/train	-	5
No. of cars	-	100
Freq. of operation	Continuous	1800m train every 105 min, daily
Personnel	335	2570
Steel, tonnes/30 yr	409,090	772,727 [†]
Fuel equiv. for Operation	1.3×10^6 tonnes coal/yr	409×10^6 liters diesel fuel/yr
Fuel cost	$\$5.6 \times 10^6$ (\$4.40/tonne)	$\$30 \times 10^6$ (8¢/liter)
Inflation rate	<1%	5.4%
Grade crossings	49 rail	750 road
Coal loss; tonnes/yr	nil	227,273
Water, m ³ /yr	18.5×10^6 (15,000Ac-ft/yr)	nil

*Source: Reference 30

⁺Excludes upgrading of roadbed, assumes no abnormal track and wheel wear, and neglects replacement costs of ties and ballast. Galey (32) claims the capitalization, including 160 km of new railroad would cost only \$350 million. Furthermore, rail would have an excess capacity of about 55 million tonnes annually over the pipeline.

[†]Does not include replacement of existing lighter rails with heavy rail.

25 million tons of coal (22.7 million tonnes) by slurry pipeline, as compared to rail, would result in savings of approximately \$14 billion over a 30-year period...."(30). One 1500-megawatt power station supplied by a coal slurry pipeline could save consumers of electricity as much as \$2 billion over a 40-year period, according to G.W. Oprea, executive vice-president of Houston Lighting and Power Company (35).

When reliability of rail transportation was cited as an advantage earlier, the means of achieving it were not detailed. At one unit train facility, (the previously-mentioned system in Arizona (36)), reliability could only be guaranteed by redundant equipment which undoubtedly increased the capital costs of the system. It can be assumed that most railroads must follow this practice to achieve a desired overall availability.

A secondary effect of coal haulage by rail centers around its manpower requirements. If western coal production expands as predicted, local populations are expected to expand with it. The railroad's labor intensiveness could have severe growth implications on small western towns that will have already experienced expansion due to the influx of mining personnel.

The environmental aspects of railroad haulage of coal also must be considered. Conservation of fuel, especially from foreign oil sources, is important in the United States. Unit trains use diesel fuel oil, which could become a scarce commodity. If coal unit train traffic increases, the dependence on foreign oil may increase also.

Conflicting land use is another aspect of railroads that should be considered. The right-of-way width for railroads is from 17m to 34m, which is similar to the right-of-way width for coal slurry pipelines (25m). However, the land occupied by the tracks and road bed are totally committed to rail transport while the right-of-way occupied by a buried coal slurry pipeline has contemporaneous land uses.

Noise pollution is a problem with unit trains. Sound levels of from 88 to 98 decibels were recorded 15m from a diesel locomotive while noise from cars in tow measured from 80 to 94 decibels at the same distance. According to one industrial safety text (37), "although no definite level of sound intensity that can cause hearing damage has been established, it is generally accepted as on the order of 85 to 95 decibels." This text suggested the wearing of ear protection for persons exposed to this intensity of noise for extended periods. Some small towns in the West have projected rail traffic of one unit train, one hundred cars long, passing by every 20 minutes, night and day, 365 days per year (38). There is hope, however, with the release of a new Environmental Protection Agency (EPA) regulation limiting the noise of diesel locomotives through the use of mufflers. The

regulation takes effect in early 1980, but the EPA estimates that it will take 25 years to replace the entire national locomotive fleet with quieter models.

The vibrational damage to structures adjacent to the tracks has yet to be studied, but it would be safe to assume that such heavy coal traffic would have some adverse effect with the passage of time on structures relatively close to tracks.

Traffic disruption is a major problem with unit coal trains. Fort Collins, Colorado, is bisected by railroad tracks. It currently experiences two unit coal trains per day, disrupting traffic for a maximum of 5 minutes each time along the 18 grade crossing on major streets. The number of trains is due to increase to twelve daily within a year. It has been estimated (39) that 11,000 automobiles will be idling each day, consuming about 3 million liters of gasoline per year. In addition, the trains are disruptive to emergency services such as fire protection, police, and ambulance operation. In Fort Collins the only hospital and most of the fire stations are on the east side of the tracks while the majority of residents they serve live on the west side. This situation may force the duplication of services on both sides of the tracks, an expensive endeavor for small and large communities alike.

Rerouting the tracks around the affected community is an alternative. At the present time this cost must be assumed by the affected community. The town of Lusk, Wyoming, is in this exact situation. In congressional testimony the following statement was made: "The townspeople were told that the railroads would be happy to build a bypass to relieve Lusk of the damage and dislocation of heavy rail traffic - as long as Lusk paid for the new right of way and all costs of relocating the line. Otherwise, nothing would be done "(40).

Rerouting lessens but does not eliminate the problem of grade-crossing related accidents. The rate of train-automobile accidents is bound to increase as coal train traffic increases. When railroads were compared to pipelines (petroleum) on a per tonne-km basis from 1963 to 1968, the railroads had approximately 220 times more accidents than petroleum pipelines (30). Railroads had approximately 1700 fatalities per trillion tonne-km during that time from all kinds of freight operations. The Federal Railroad Administration (41) lists 910 fatalities from railroad-highway crossing related accidents during 1975. The number in 1974 was 1221. The annual average over the past 10 years is 1444. There are 401,000 public and private grade crossings in the country. In 1975 the total number of train accidents was 7895, representing a 5.4% increase over the previous year.

A bill was introduced in 1977 (42) to limit the length of freight trains to 1310 m (about 75 cars) to improve safety and

TABLE 10. RATIO OF EQUIPMENT FAILURES BASED ON TRAIN LENGTHS*

Failure	<75 cars	>75 cars
Burst air hoses	1	3
Sticking brakes	1	8.5
Coupler failure	1	7.4
Train delays	1	1.5

*Source: Reference 42

reliability by reducing derailments and equipment failure. Table 10 shows the relative increase in frequency of equipment failures on long trains versus short trains. If long trains are made illegal, the manufacturers will not be able to make larger cars because of axle loading limitations.

An additional hazard associated with train operations is fire. Sparks coming from locomotive emissions, hot boxes, brake shoes, and maintenance crew operations can start fires along the right-of-way in weeds, brush, and spilled coal. Rail operations and lightning have been noted to be the two leading causes of fire within Campbell and Converse Counties, Powder River basin, Wyoming (30).

Environmental impacts on the railroad right-of-way are also felt through the use of weed control agents. Railroads have used chemicals such as 2-, 4-D, and 2-, 4-, 5-T for this purpose. These agents are rated fourth on the USDA Toxicity Rating Chart.

Furthermore, coal is deposited along the right-of-way. It has been estimated (43) that a unit train can lose 1% of its coal on a haul of 1600 km. That represents approximately one car load or 90 tonnes lost for each train unless a binder is used to control fugitive dust.

One problem common to many western coals is their susceptibility to spontaneous combustion. Since railroads are labor intensive, they are subject to occasional strikes. These two factors combine to become a potentially dangerous situation. A rail strike would not have to last long, perhaps only a week, for any loaded coal cars to ignite spontaneously. A coal-water slurry pipeline has virtually no chance of experiencing spontaneous combustion because of the lack of air and the high water content.

In short, these detrimental aspects of rail transport probably cannot be completely eliminated but should be minimized in every available way. The fact that railroads are not presently required to file any kind of environmental impact statement before their proposed increase of unit coal train traffic (44) should be a point for future consideration and assessment.

Mine-Mouth Power Generation and Extra-High Voltage Transmission

The use of mine-mouth power plants to generate electricity and deliver it to consumers via transmission lines is another way of moving the energy found in coal. Mine-mouth power plants are numerous, particularly in the Appalachian coal fields if there exists a major river to supply cooling water and if other transportation modes are difficult.

It would appear that moving electricity generated at the mine mouth would amount to substantial savings, but it has been found that Extra High Voltage Transmission (EHV) can be a more expensive method of moving energy than either unit trains or coal slurry pipelines (45).

Environmental aspects of mine-mouth power generation must also be considered. A power plant generally has an adverse environmental impact that adds to the impact of mining operations. In addition to land use allocated to mining activities such as preparation plants and mine refuse disposal, there must be added land use for evaporation ponds or cooling towers, additional use of water for cooling, and facilities for collection and disposal of fly ash, bottom ash, and possibly scrubber sludge. Stack emissions and cooling tower evaporation may have an adverse effect on the local atmospheric conditions and reduce the aesthetic appeal the area may have.

Transmission lines and smokestacks can be dangerous to local air traffic or may disrupt air traffic patterns. On the ground transmission lines are aesthetically undesirable in rural settings, and land use may require alteration.

Transmission line right-of-way is almost 200 meters wide compared to 17 to 34 meters for railroads and 25 meters for coal slurry pipelines. However, unlike the case of railroads, lands traversed by transmission lines can support some land uses such as agriculture with little acreage actually lost.

Deleterious health effects from electromagnetic fields near EHV transmission are not fully understood.

Barge Transportation

About one-quarter of U.S. coal production moves by barge. Barge transportation is obviously limited geographically to the rivers and canals of the United States (Figure 3) (46). The majority of the inland waterways are found in the central and eastern United States and barge transportation, therefore, is not useful to deal directly with any western coal expansion. However, it is conceivable that a unit train unloading site or a coal slurry pipeline terminus could be located on a major river where the coal could be transferred to barges for waterway trans-

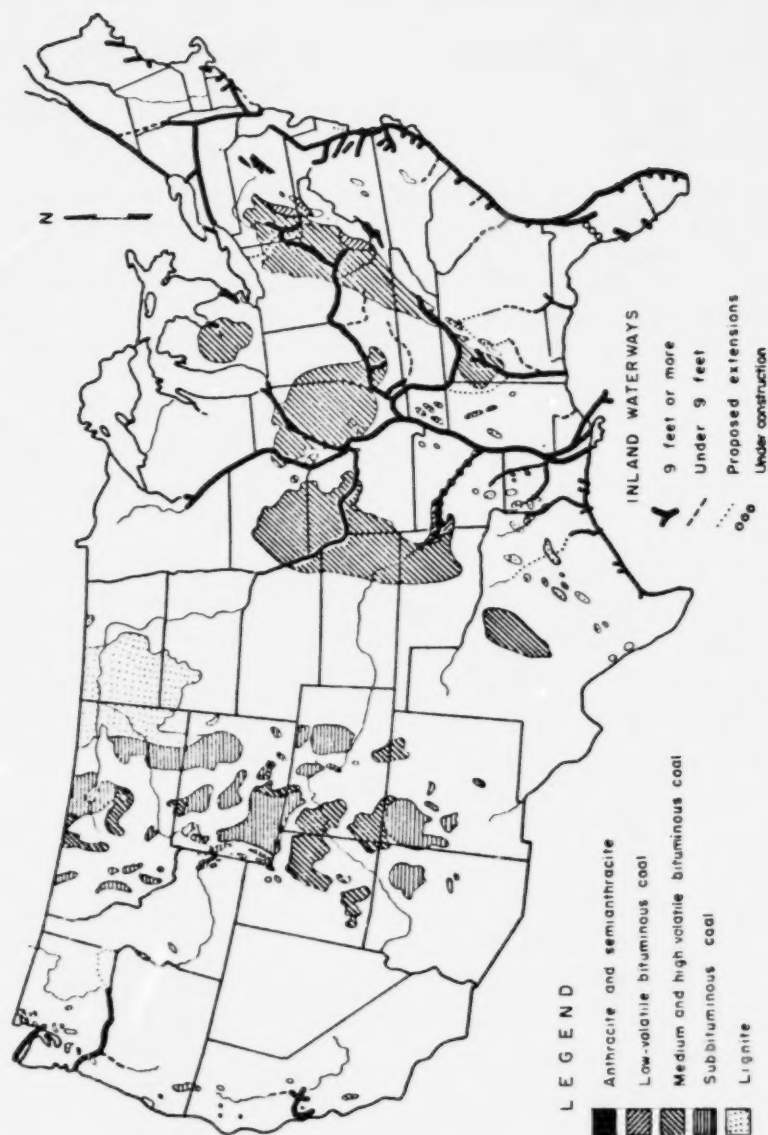


Figure 3. Coal deposits in relation to inland waterways. (46)

port to several consumers.

Barge transportation is the least expensive mode of coal transport (Table 11). Although the costs are stated as 1972 dollars, they provide a comparison of coal transportation costs.

Barge transport has historically been cheaper than rail transport despite the additional miles created by circuitous waterways. This may change in the future since unit trains move more coal at faster speeds.

The disadvantages of barge transport include slow speed and inflexible routing. In addition, special unloading facilities are required, and loads are based on tow sizes which are limited by chamber size of locks in navigable waterways while drafts of barges are limited by controlling water channel depth. Though some coal barges hold up to 1800 tonnes, the majority hold only 1300 tonnes. It appears that this transport mode will see limited growth as waterways become increasingly congested and polluted. Growth in coal barge transport traffic on the Mississippi River is expected to peak in 1980 (46), the greatest growth expected in the South as efforts are made to promote southern coal exports to Japan.

River maintenance operations that must be performed by barge companies presently do not amount to much as almost all the rivers, locks, and dams as well as other navigational necessities are maintained by the U.S. Army Corps of Engineers. This will probably be the case for years to come, but the barge companies may be subject to a river use tax in the near future that would

TABLE 11. COSTS OF COAL TRANSPORTATION(1972 ESTIMATES)*

Type	Costs (dollars per 10 ¹² BTU transported)			Distance assumed (km)	Cost, cents/ tonne-km
	Fixed	Operating	Total		
Unit train	5,100	79,800	84,900	480	0.5
Conventional train	9,240	145,000	154,000	480	0.9
River barge	4,850	35,600	40,400	480	0.2
Slurry pipe- line	48,500	20,800	69,300	440	0.4
Trucking	1,850	16,700	18,500	16	3.1
Conveyors	10,500	5,100	15,600	8	5.2

*Source: Reference 47

supposedly be used to improve and maintain the rivers and other inland waterways of the United States.

The other major difficulty that barges must contend with is the weather. On occasion barge traffic can be stopped due to ice conditions for as long as several weeks. Occasionally, drought conditions can lower water levels, thereby necessitating a reduction in barge loadings.

Short Distance Transport Modes--Trucks and Conveyors

Truck transportation is a method of moving coal used when the distance to be covered is quite small. Truck hauls of tens of miles have been known, but were used only as short-term solutions while more permanent answers were being sought to particular transportation problems.

For the short haul trucks are flexible, but they have relatively short equipment lives and require good roads, good weather conditions, and skilled operators to function efficiently. It is not economical to use trucks over long distances. Also, their use might damage public highways with their increased loads.

For high-volume truck hauls, the overall work efficiency of haulage is about 68-77% (48,49). Work efficiency of haulage does not include maintenance downtime but does include time lost due to queuing and refueling. The empty return haul is included as operating time.

The maximum capacity of trucks for coal operations is 77 tonnes in the East and 155 tonnes in the West. Eastern coal mining operations are more selective because of the thinner seams while western operations must contend with much thicker seams. Western trucks have unitized bodies of the tractor-trailer type with over-size hoppers and bottom-dumping capabilities (48).

Conveyor belt systems are also a short distance, high-volume mode of transporting coal. Presently existing are lengths of up to 30 km and widths to less than 2 meters. Aspects to be considered include the fact that some system components have short life spans. The systems are usually above ground and aesthetically undesirable, and they are exposed to the elements. Maintenance of a mechanical coal transportation system is also critical.

While Table 11 shows truck transportation costs to be cheaper than conveyors, another comparison shows the reverse (49). It was found that, based on a copper mining project, conveyors can be more efficient energy users, less sensitive to inflation, and less labor-intensive than trucks.

Efficiency and Economics

A comparison of energy efficiencies of the various transportation modes is always open to question regarding assumptions made. For instance, the author's own calculations for the Black Mesa coal slurry pipeline show an energy requirement less than one-half of that given in Table 12. Also, it is not known if the truck and rail cases included an empty return haul.

The primary efficiency is the percentage of product lost through wind and spillage. A slurry pipeline has no spillage in normal operation, but its product does gain moisture. At Black Mesa the mined coal has a moisture content of about 11% which increased through slurry transport to 39% at the power plant boiler after dewatering. Future improvements in the dewatering stage are expected to reduce the final moisture content to 32% (17). Thus, the primary efficiency of 98% for the pipeline given in Table 12 is much too high.

Though it is not the intention of this report to examine economics in detail, it is probably fair to say that total transportation project costs must bear some relationship to environmental impact. As project cost decreases, perhaps the environmental impact does too. On that basis, it is interesting to compare the transportation costs in a recent study by Banks and Leemans (50). They compared the transportation of energy blocks of 1600, 3200, 6400, and 9000 MW increments over distances of 500, 900, and 1500 miles by rail, barge, pipeline, and transmission lines. They concluded that the pipeline coal-energy transportation system in 11 of 12 cases was the most economical means of transporting energy. Except for large energy blocks at long distances, rail-barge transportation systems, as defined in the study, were the second most attractive alternate. Railroads, in half of the cases studied, proved to be the most expensive means of transporting energy.

Pneumatic Pipelines

The transportation of coal over long distances by pneumatic pipeline is generally agreed to be uneconomical at present, but it may be a viable alternative in the future (51,52,53,54,55).

From a technical and economical point of view, water is presently the most desirable lubricant or carrier for the pipeline transport of coal. However, if western coal and western water are considered incompatible, the temptation to utilize air as a carrier vehicle is very strong.

Air is free for the taking and poses no de-watering problem. However, the pneumatic pipeline transportation of coal is neither technically nor economically feasible for long distances with present-day technology. Air does not have adequate viscosity and

TABLE 12. COAL TRANSPORTATION ENERGY EFFICIENCIES*

Method and Location	Primary efficiency (percent)	Ancillary energy requirement (10 ⁹ BTU's per 10 ¹² BTU's transported)	Average haul distance (km)
Unit trains	99		
Northwest		9.9	241
Central		15.8	467
Northern Appalachian		15.8	515
Central Appalachian		18.7	636
Southwest		5.89	161
Mixed or conventional train	98		
Northwest		7.82	241
Central		12.5	467
Northern Appalachian		12.6	467
Central Appalachian		10.7	443
River barge	98		
Central		8.9	483
Northern Appalachian		21.3	1287
Central Appalachian		7.76	483
Trucking	99		
Northwest		1.27	16
Central		1.07	16
Northern Appalachian		0.96	16
Central Appalachian		0.93	16
Conveyor	99		
Central		0.42	8
Northern Appalachian		0.37	8
Central Appalachian		0.38	8
Slurry pipeline	98	7.09	439

*Source: Reference 47.

density to support coal particles in suspension to the same degree as water does, even when the coal is pulverized. Low pressures, high velocities and hence large air flows are necessary to keep the coal in suspension. This is called dilute-phase (low solids concentration) flow. For pulverized coal the velocity can be reduced, but the pressure drop increases. This is called dense-phase (high solids concentration) flow. Both types of flow regimes consume large amounts of energy in conveying the coal in addition to the cost of collecting and compressing the air.

For instance, the author has shown elsewhere (53) that for coarse aggregate the specific power (kw-hr/tonne-km) for slurry transport is about one-tenth that for dilute-phase pneumatic transport by pipeline. Presumably coarse coal would give a similar comparison.

Also, coal feeders and air blowers or compressors are not presently available in the sizes necessary for the high throughputs envisioned for overland transport by pipeline. Existing pneumatic pipelines seldom extend for more than 300 meters and typically transport less than several hundred tonnes per hour. Proposed coal slurry pipelines are expected to traverse a thousand miles overland and to carry several thousands of tonnes of coal per hour.

The safety of transporting coal pneumatically by pipeline has been questioned. The U.S. Bureau of Mines has been trying to establish a guideline for permitting pneumatic pipelines in underground coal mines. None exists in the United States to the author's knowledge, but several are working in the United Kingdom (52,56). The higher methane levels in eastern U.S. Mines are offered as a reason for possible methane gas explosions in pneumatic pipelines. Although unproven, it has been hypothesized that a coal pneumatic pipeline leaking coal dust less than 0.8mm in size in a local concentration of 80 grams per cubic meter next to an ignition source could cause an explosion (57). A recent U.S. Bureau of Mines publication (58) suggests that combinations of coal dust and methane are explosive mixtures but are unlikely to be ignited by tramp rock or metal flowing in a pipeline.

Having considered some of the effects of the alternate coal transportation modes, this writer will now examine the environmental aspects of slurry pipelines.

SECTION 3

WATER QUANTITY AND QUALITY

Water is the Achille's heel of a slurry pipeline. Without it, there is no slurry pipeline. Although water is our most abundant resource, it is not always found where it is needed. In a sense water is akin to energy because it is neither created nor destroyed but transformed between its three phases: solid, liquid, and gas. The hydrologic cycle of precipitation, runoff, infiltration, transpiration, and evaporation--demonstrates this principle of transformation.

Because water is our most essential human requirement, it becomes a controversial issue whether the application is recreation, hydroelectric power, irrigation, or energy transportation by pipeline. The quest for domestic energy independence by substituting coal for oil and gas will require water. Whether coal is burned directly in powerplants or converted to gas, liquid, or upgraded solid fuel, vast quantities of water will be required.

Coal slurry pipelines are a proven technology and are a competitive mode of transportation for moving coal. Its carrier liquid should be abundant and inexpensive, and its use should entail minimum adverse environmental impact. From a technical and economical viewpoint, water is presently the most desirable lubricant for the pipeline transportation of coal. It is the most readily available fluid even in the semi-arid West. Hydrocarbon carriers such as oil have not been found in economical quantities near a source of coal. A heavy gas such as pressurized carbon dioxide is expensive to collect and compress and does not support coal particles in suspension for economical transport by pipeline to the same extent as water. Methanol derived from coal looks promising as a coal carrier, but many technical and economical questions must be answered before this transportation mode becomes viable. Hydrocarbon carriers are discussed in more detail in Section 7.

This section examines the amount of water required for a coal-water slurry system and comments on the quality of available water.

WATER QUANTITY

The quantity of water necessary for a coal slurry is determined from two factors: annual throughput (usually expressed in million tonnes) and solids concentration. The concentration by weight of coal is C_w , the weight ratio of dry coal to that of slurry (dry coal+water).

Long-distance coal slurry pipelines have transported coal concentrations from 40% to 60% by weight, usually averaging just under 50%. For convenience in further calculations, $C_w=50\%$ will be assumed, giving the following simple relationship: 1 tonne of coal requires 1 tonne of water to produce a coal-water slurry. Table 13 lists various relationships for the amount of water required based upon a 50% weight concentration. These requirements are applicable to any coal regardless of its calorific value. When comparisons are drawn between water requirements for alternate energy transportation modes, the heat content must be considered for an unbiased assessment of the different requirements.

The higher the water requirements are for a particular energy system, the more environmentally upsetting that system is. Table 14 summarizes the water requirements of various transportation modes (59).

A small amount of additional water would be required by the pump stations in a slurry pipeline system for cooling transmissions and motors and as a flushing medium to keep solids in the slurry from scoring the shaft, piston rods, or plungers in the pumps.

Positive displacement (PD) pumps have been used to pump coal slurries over long distances. Though they are low-flow capacity pumps, they develop high pressures suitable for long-distance pumping. To obtain high flow rates, PD pumps are placed in parallel.

The Black Mesa pump stations use typically 1.6 l/s of water from their storage pond for evaporation, pond seepage, and cooling. In warm weather approximately 80% (1.25 l/s) is lost to evaporation. Thus, the maximum water requirement per pump station represents about 1/2% of the total slurry flow (or about 1% of the water carrier flow).

The pipeline operation requires $3.95 \times 10^6 \text{ m}^3$ of water per year. Flagstaff, the city closest to Black Mesa, uses about $8.63 \times 10^6 \text{ m}^3$ per year. These consumptions are insignificant compared to the evaporation loss (estimated at $802 \times 10^6 \text{ m}^3$ per year) from Lake Powell on the Arizona-Utah border.

The piston pumps at Black Mesa use recirculating flush liquids consisting of soluble oil and water or diesel oil and water.

TABLE 13. WATER REQUIREMENTS FOR 50% BY WEIGHT COAL SLURRY

Coal	Water
1 kg	1 kg
1 tonne	1 tonne
1 lb	1 lb
5×10^6 ton/yr	3,678 Ac-ft/yr=4,536,813 m ³ /yr
15×10^6 ton/yr	11,033 Ac-ft/yr
25×10^6 ton/yr	18,389 Ac-ft/yr
1 ton/hr	3.994 gpm=0.008993 cfs=5812 gal/day
1 tonne/hr	0.0002778 m ³ /s, 0.27783 l/s
5×10^6 tonne/yr	5×10^6 m ³ /yr

TABLE 14. WATER REQUIREMENTS OF VARIOUS ENERGY TRANSPORTATION ALTERNATIVES*

Alternatives	Water Requirements	
	m ³ /joule	Tonnes Water Tonnes Coal
Gasification	26 to 57	0.6 to 1.32
Liquifaction	11 to 72	0.26 to 1.66
Mine Mouth Power	305	8.0
Plant(Wet Cooling Towers)		
Unit Trains	nil	nil
Barges	nil	nil
Trucks	nil	nil
Conveyor Belts	nil	nil
Pneumatic Pipelines	nil	nil
Slurry Pipelines(C _w =53%)	38	0.89

*Source: Reference 59

Data assumes a heat value of coal of 10,000 BTU/lb.
(23,250 Joules/gram)

Approximately 114 liters are used in a closed circulating system to flush the pump glands.

Water Resources

America is said to be one of the few countries with relatively abundant water supplies. However, in light of recent problems involving the use and pollution of our water resources, Americans now realize that water is a very precious commodity and must be used wisely. A high standard of life is a prized possession to all Americans.

Energy production is the common bond between these two entities: water and living standards. Water is a primary necessity for life, yet it is also necessary for the continuance of heavy industry. Amounts of water allotted to industrial, agricultural, municipal consumers must be balanced. It is easy to assume that agricultural and municipal use takes precedent over industrial use, but farms and municipalities could not function without the heavy equipment and power provided by industry. Figure 4 illustrates the various water uses in the United States.

In some states agriculture utilizes the lion's share of water but contributes a smaller percentage of revenue to the state than industrial sources. In Colorado, for example, 1976 statistics indicate that agriculture contributed approximately 6 billion dollars in cash receipts to the total of approximately 21 billion dollars of gross state revenues and employed almost 17% of the state's labor force. However, agriculture consumes 92% of the total water in the state (61,62). Viewed in this way, therefore, the role of water--its worth and priorities--may have to be re-evaluated in the near future, especially if a state chooses to increase energy production at the expense of agriculture. In order to balance water usage between industry and agriculture, it will be necessary to attach more importance to water conservation. For example, irrigation systems incur tremendous losses to evaporation and seepage. Figure 5 shows the relative amounts that are lost and used for irrigation. The water saved by improved irrigation practices and ditch lining could be utilized by energy producing or energy transportation industries. The laws governing water allocation may have to be changed to benefit all users: industrial, agricultural, and municipal. Water allocation laws vary from state to state. Perhaps a uniform set of water allocation laws is needed in the western states to assure the proper development of energy resources without detrimental effects on other users of water.

Groundwater

Water covers 75% of the total surface area of the earth. It is found in oceans, rivers, lakes, polar ice caps, and underground in the form of aquifers.

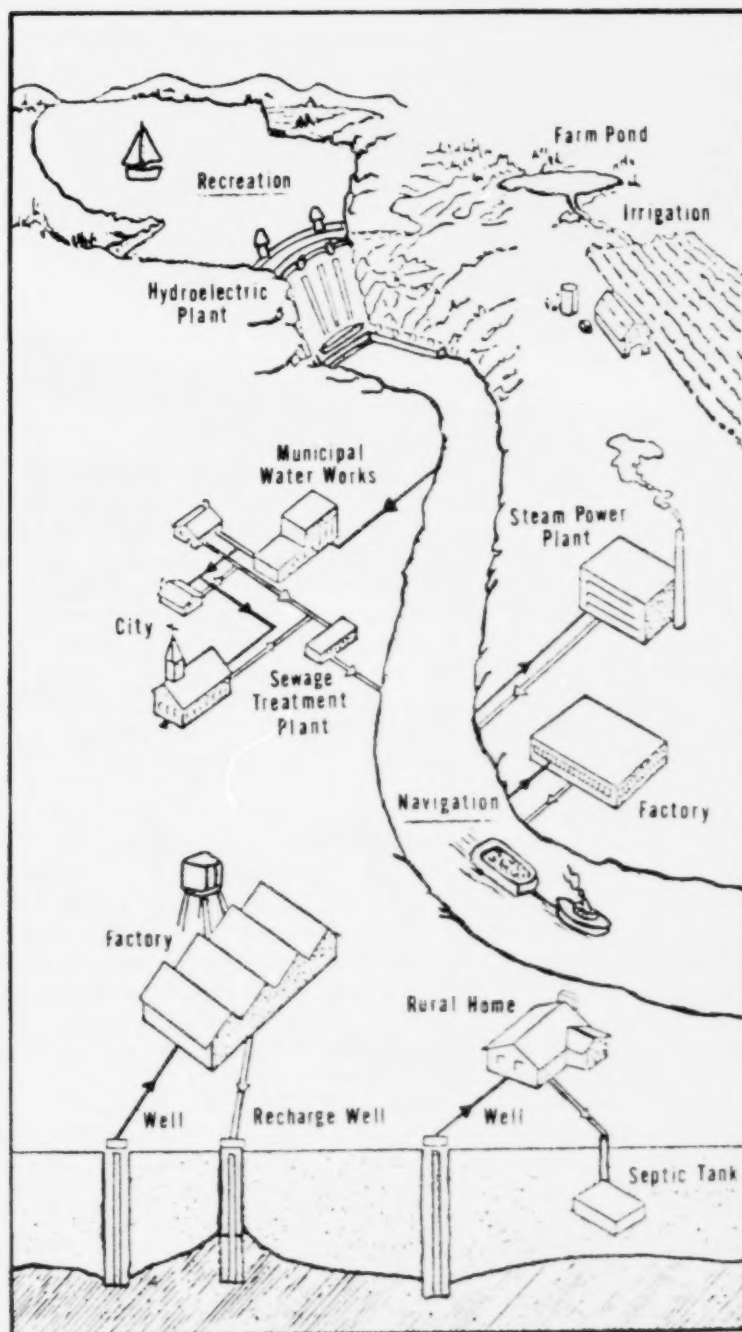


Figure 4. The many uses of water in the U.S.A. (60)

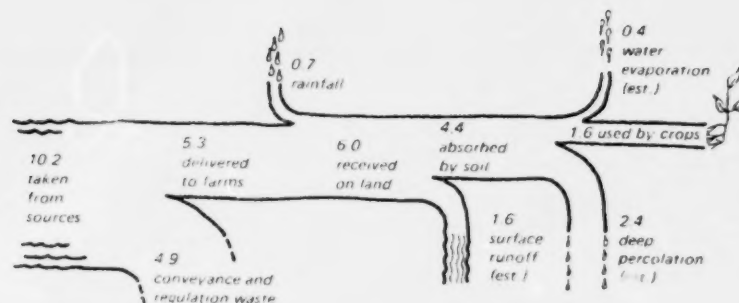


Figure 5. Disposal of water diverted and pumped for irrigation (relative values).(60)

An aquifer is a porous, water-bearing rock formation whose pores are connected so that the formation is considered permeable. The ability for water to flow through these pores is called transmissivity. The water-bearing aquifer can be shallow or deep beneath the earth's surface. The water can be obtained from springs if the aquifer is shallow and topographic conditions permit. If the aquifer does not intercept the surface, water can be obtained through wells drilled to the aquifer. Sometimes local pressures allow the water to flow out of wells, but most often the water must be pumped to the surface. The principal aquifers of the United States are illustrated in Figure 6.

An aquifer very much in the spotlight at present is the Madison limestone formation that underlies the Powder River Basin in Wyoming and parts of Montana, and South Dakota. Energy Transportation Systems, Inc. (ETSI) plans to use water from this aquifer (48.7×10^6 hectares) for their coal slurry pipeline to Arkansas. The hydrological implications of this project are immense (63). Many reports have been written about the Madison aquifer and indicate various opinions about the amount of the impact that the removal of water from the Madison will have on groundwater supply of the Northern Great Plains.

The following quote from a USGS map of various Madison geological features illustrates recent use of water from the Madison (64):

According to the Wyoming State Engineer (1974) about 30.8 million m^3 of water was withdrawn from the Madison in the Wyoming part of the Powder River Basin in 1973. The Madison is the principal source of water for secondary recovery of oil in the Powder River Basin in Wyoming. More than 24.7 million m^3 was used for se-



Figure 6. Major aquifers in the U.S. (60)

condary recovery of oil and about 3.7 million m³ was used for municipal water supplies. Other water use from the Madison includes about 1.2 million m³ per year in the Osage-Newcastle area for electric power generation and for oil refinery water requirements.

A major problem is predicting the behavior of an extensive aquifer when it is stressed by the removal of 18.5 million m³ of water per year as proposed by ETSI.

The USGS is attempting to address these problems in a study of the Madison formation. At the time of this writing, the study is in the second year of the five years expected for completion. The study does not necessarily deal with the requirements for a slurry pipeline. Rather, it deals with water quantity and quality in the Powder River Basin without regard to who will actually use the water and how.

The study has the following objectives: (63)

1. To determine the quantity of water that may be available from the Madison aquifer.
2. To define the chemical and physical properties of the water.
3. To determine the effects of existing developments on the potentiometric head, the storage, the recharge and discharge, the springs, the streamflow, and the pattern of ground-water flow.
4. To predict the probable hydrologic effects of proposed withdrawals of water for large-scale developments at selected rates and locations.
5. To determine the locations of wells and the type of construction and development of deep wells that would obtain optimum yields.
6. To design a network of observation wells and stream gages to monitor the effects of additional developments of the hydrologic system.

According to Elliot Cushing, the engineer in charge of the project, the primary goal is to define adequately the Madison with a computer model to predict accurately the results of pumping for a number of years. The USGS is attempting to find the best area in the basin to drill wells. The selection of this area is a function of many factors but is primarily concerned with the depth of the formation and with predicted yield rates.

A computer model of the Madison aquifer was formulated (65), using the existing scarce data available before actual planning of drill sites and gathering of additional data, which will take place during the five years planned for the study. The purpose of this model was to aid in gathering data to show where critical information was lacking. Remembering that a computer model is only as accurate as its input data, many assumptions were re-

quired to formulate the model, and it will be these assumptions that will be checked in the data collection. As more data are collected, the accuracy of the model will be improved.

Mr. Cushing notes that every energy development project requiring water need not go into as much detail as the USGS has in the case of the Madison aquifer. The reason for the modeling of the Powder River Basin stems from the basin's sheer vastness, posing a complex problem of understanding interrelated variables.

To satisfy most State agencies the hydrology of the water source must be known, including information about objectives outlined by the geological survey. The time and cost of such an endeavor would probably vary directly with the extent and complexity of the aquifer studied. The cost of the USGS 5-year plan was estimated at 11.4 million dollars for this area of about 49 million hectares (63).

The amount or capacity of water that a particular aquifer can hold is generally finite; and if the extensive hydrological studies suggested previously are performed, this capacity is roughly calculable. While removal of water from an aquifer generally lowers the water table in the vicinity of the well in what is called the drawdown cone, the aquifer will not necessarily be drained dry.

Most aquifers intersect the surface at some point and receive surface water in the form of runoff or snow melt in the spring. The recharge of the aquifer with new water is generally a continuous process. However, if the rate of removal of water from the aquifer is greater than the recharge rate, groundwater mining results, and the aquifer could dry up and the water table could be permanently lowered.

The water permits granted to ETSI by the State of Wyoming have the following stipulations: (66)

If the permittee lowers the water table, the permittee has the choice of:

- 1) Deepening the wells and paying for damages which may include extra cost of water for farmers,
- 2) Supplying water to people whose water supply was decreased when the water table was lowered,
- 3) Obtaining its water elsewhere.

The permittee will pay the costs of court and reasonable fees of attorneys and experts of any person who is required to enforce the terms of this permit by legal action, provided said person is successful in obtaining a final judgement in his favor and against the permittee. The permit may be terminated by the state engineer if

the water table is endangered. This decision can be contested in court.

In 1971 the U.S. Geological Survey initiated a groundwater monitoring project to determine the magnitude of declines that can be attributed solely to the pumpage from the Peabody well field at Black Mesa. Four observation wells were drilled in 1972 and another was available in the community of Kayenta. By January 1977 two wells showed no change, two showed a decline of about two meters, and the fifth (in Kayenta) showed a steady decline since 1967. Most of the decline, however, is probably caused by the increase in municipal pumpage required to support an increasing population. The data are not considered conclusive evidence about water quantity. No changes in water quality have been detected to date (67).

An aquifer could be artificially recharged by drilling down to the aquifer and injecting surface water to replace water removed elsewhere in the aquifer. A pipeline firm could pump water from an aquifer at one point while at another it could inject water into the same aquifer from a flood-swollen river on the surface. It would lessen the possibility of groundwater mining and could supply the slurry water requirements at a different location without the necessity of building overland pipelines to the origin of the slurry pipeline. Obviously, the groundwater profile must be defined completely before this type of flow exchange can be implemented.

Another source of underground water might possibly be mine wastewater, which is generally acidic. The removal of this water from an area would benefit any local water shed. The application of this idea is not generally practised because the presence of this type of water source is usually localized. Nevertheless, if conditions permit, the use of this source of water should be considered. It does, however, present other problems.

Water Rights

The procedure for obtaining water rights in the West is quite rigorous. For example, in Colorado, water rights are determined by meeting several burdens. These burdens are designed to assure that water appropriation and use will help to maximize the beneficial use of all the waters of the state in accordance with the well established principles of the appropriation doctrine:

- (i) Waters of the state are the property of the public, dedicated to the use of the people of the state;
- (ii) The right to divert the unappropriated waters of any natural stream to beneficial uses shall never be denied;
- (iii) Priority of appropriation shall give the better right as between those using water for the same

purpose--first in time is first in right.

Wisely, the doctrine does not establish a priority list of water use. The third and first principles allow for re-allocation of water to energy production and transportation once people are convinced it is to their benefit to do so. Once the transfer of water rights from agriculture to the energy industry looks feasible, it is the onus of the energy industry to define the environmental impact of their proposed project. A water rights applicant must negotiate a rigorous obstacle course marked along the way by challenges from numerous adversaries, both public and private. Therefore, it is not surprising that water for a coal slurry pipeline is sought from groundwater sources, which are more apt to be unappropriated and non-tributary to other surface or underground water rights.

Surface Water Sources

Since surface water is visible, it does not present the same degree of difficulty as groundwater when defining its quantity and quality. Furthermore, most surface waters are already allocated to agriculture, industry, and municipal users.

Surface water is much cheaper to utilize than underground water sources. It is obvious that the costs of drilling deep wells to aquifers and pumping the water to the surface are much higher than diverting a stream or river into an irrigation ditch or piping water a short distance from a reservoir. Therefore, the use of surface water for coal slurry pipelines should be considered before proceeding to drilling programs that tap aquifers. The principal source of surface water is precipitation. Water in the form of runoff not absorbed by the soil, evaporated, and utilized by plant life flows into streams which may feed rivers or lakes in a watershed. Water is used and reused many times on its journey to the sea in rivers. When runoff is excessive, such as in the case of the entire Mississippi watershed almost every spring, it could be diverted to other beneficial uses, at the same time minimizing the possibilities of downstream flooding. Diversion of water from flood control dams to coal slurry pipelines would constitute a beneficial use. Since a drought could occur at any time the use of surface water for coal slurry at such times might conflict with higher priority usage. Therefore, both surface and groundwater supplies may be desirable for a coal slurry pipeline to ensure water availability during the life of the project.

Other possibilities should also be investigated: first, the utilization of municipal or industrial waste water after primary or secondary treatment; second, the prospects of joint use of water supply pipelines with municipalities; third, the use of contaminated mine water; and fourth, the use of brine or salt water. The use of these alternatives involves additional enviro-

onmental and engineering considerations which will be discussed subsequently.

Recycling or recirculation of the water carrier has been suggested as a means of conserving water. This involves taking the water from the separation plant and--instead of sending it as cooling water to the power plant--transporting it by pipeline back to the preparation plant at the head of the pipeline.

Odasz (68) of ETSI claims that the annual 18.5 million m³ of water required for the Wyoming-Arkansas coal slurry pipeline could have been purchased from the Oahe Reservoir for \$0.97/m³, or that a recycle line could have been built from Arkansas to Wyoming at a cost of \$2.84/m³ for the water returned. In addition, the recycle line would need 267,000 tonnes of steel and a continuous power consumption of 39,000 kw to return the water uphill. Neither of these alternatives is attractive since the cost of water from the wellfield is estimated at \$0.32/m³. The cost of recycling water would be prohibitive, and the slurry pipeline would not be economically competitive. The material required to build the return line and the energy needed to return the water would not be environmentally advantageous from the viewpoint of total conservation of resources.

The economic advantage of a slurry pipeline results from high throughput over long distances with a high use factor. Anything disruptive of these three aspects weakens the economic advantage. Since the cost of steel pipe comprises a substantial portion of the total cost of the project, any additional pipe length also weakens the economic advantage.

WATER QUALITY

After considering the possible water sources for a coal slurry pipeline, the quality of water from those sources should also be examined. The maintenance or improvement of the original water quality after its use should be the goal of any pipeline operator.

There are four groups of variables that help to define the quality of water: 1) physical, 2) chemical, 3) microbiological, and 4) radiological characteristics. The variables include: taste, odor, color, turbidity, temperature, dissolved oxygen, chemical oxygen demand, pH, dissolved organic and inorganic chemicals including pesticides, dissolved and suspended solids, biological oxygen demand, total oxygen demand (the sum of biological and chemical oxygen demands), coliform organisms, fecal coliforms, and the various types of residual radioactivity. Some of these variables overlap with other variables--for example, when color, turbidity, and total oxygen demand are combined.

The U.S. Department of Health has standards for public drinking water that define exactly the amounts of the above variables that are allowable or desirable (see Appendix B).

By comparing the quality of water to be used in a slurry pipeline to the water quality standards for other uses, the alternate uses of the water source in question can be determined. This comparison is important because the development of a particular geographical area may hinge on the availability of water for certain types of consumption. If a source of unallocated water is high quality according to the public health standards for drinking water, it should be retained for a domestic water supply first. This would encourage population growth in any municipality with access to the supply. On the other hand, the water quality may be poor so that it can be used only for agricultural consumption--irrigation or livestock watering. If a new water supply can be treated at some cost to bring the quality into the range of municipal use, a community may want to limit its growth potential as an industrial town but encourage its growth potential as an agricultural community. The difference between agriculture and industry could hinge on water quality. There are, of course, other factors that would affect such a decision, but these are beyond the scope of this report.

Ideally, the water proposed for a slurry pipeline should have few alternate uses. For example, a high amount of dissolved solids may make water unfit even for irrigation. An amount of total inorganic dissolved solids above 500 mg/liter makes water unfit for watering livestock (Appendix B). Furthermore, water having from 1000 to 2000 mg/liter of dissolved solids may produce adverse effects on many crops unless careful agricultural management practices are followed (60). It should be noted that some municipalities in the West drink water that is supposedly unfit for livestock consumption (40).

Before any alternate uses for a water source can be determined, a series of water quality tests should be performed. The water quality variables that would most concern the operator of a slurry pipeline are those that may affect the flow and corrosive properties of the slurry and the combustion of the coal. These are dissolved oxygen, pH, trace chemical constituents, and dissolved and suspended solids. Treatment of the separated water for cooling at the power plant is required regardless of the initial quality of the water in the slurry. A method for separating and identifying the six groups of organic compounds has been developed by Leenheer (69). This method, which takes two days and requires a 200 ml sample, involves the fractionation or separation of the organic constituents found in a particular water sample. Using this method and standard water quality tests for inorganic compounds, the determination can be made of any water quality change after transport with coal. Concentrations of trace inorganic substances then can be compared to a tabula-

lation formulized by Gough and Shacklette (70), and the effect of the trace elements on water quality can be assessed.

In the slurry pipeline projects under consideration, there would be no discharge of slurry water into local watersheds. For example, the Mohave Plant in Nevada is served solely by a coal slurry pipeline and observes this practice. The entire liquid component of the slurry--minus whatever moisture that remains on the coal--is used for condenser cooling water, which constitutes about 11% of the amount necessary at the power plant (9). However, the water remaining from the slurry dewatering should be analyzed to determine its possible alternate uses and if it could be safely discharged into adjacent watersheds. In other words, water quality should be monitored both before and after slurry transport to determine any changes.

The quality of water has other effects on engineering parameters associated with the operation of a slurry pipeline system. The effects of low-quality water should be examined both from a total environmental and engineering viewpoint (44):

Coal slurry pipelines can use a variety of waste water. Sewage water, steam condensate, rain or snow runoff, brines and even ocean water might be used to make up the slurry. It is doubtful if any urban area would object if the mine operator volunteered to accept the pretreated sewage of the entire municipality. Such water would not detract from the thermal or ignition qualities of the coal. The slurrying of coal and waste water would in many cases provide "primary treatment" advantages to both.

Coal grains, washed and tumbled in settled sewer water are leached of some of the soluble minerals and volatile acids, and the ash content of the coal is reduced. Sewer water is essentially detoxified by percolating through coal; most bacteria are analysed and many cations and anions are precipitated. Surfactants, proteinaceous and fatty acid materials are inactivated or bound to the coal material. The coal and all the solids or semi-solid organic material which adheres to it are readily burned with a gain in BTU content. The waste water is essentially purified with its contact with the coal and simple centrifugation and pH adjustment will usually render the water suitable for other uses.

Simply put, the coal in the slurry may act like activated charcoal adsorbing some of the harmful constituents of the water during transportation. It is reasonable to assume that the finer the coal particles, the better the adsorption will be because of the increased surface area available.

There is also the possibility that the chemicals adsorbed onto the coal particles may go up the stack when the coal is burned. This point has not been proven either way, but it may be that trace elements or compounds are left behind with the bottom ash.

Buck (44) contends that halides in saline water are easily vaporized in the combustion chamber. In essence, a water quality problem, then, is changed to an air quality problem. In addition, the ash content of the coal would be increased from the metallic ions of magnesium, manganese, and sodium.

A substantial amount of saline groundwater is said to underlie the western states as a result of residues from ancient geological periods when the area was covered with salt water seas. Table 15 classifies saline water according to total dissolved solids.

Evans and Rice (10) have considered the use of saline water for coal slurry pipelines and have made the following observations:

1. Saline water in the West exists at depths of from 150 to 300 meters.
2. The Madison aquifer contains water with salinity averaging between 1000 and 3000 mg/l. Salinity constituents are primarily sodium bicarbonates and sodium chlorides in the eastern half of the Madison and sodium and calcium sulfates in the western half of the formation.
3. Saline groundwater cannot be pumped from the western states indiscriminately and indefinitely. It is possible in the western states to find saline aquifers overlain by fresh water aquifers that are not hydrologically isolated from each other. Pumping of the saline strata might cause flow changes in the fresh water aquifer or even intrusion of the fresh water into the salt water. Other possible environmental consequences of salt water pumping include land subsidence similar to that caused by oil and gas withdrawal and contamination of moderately saline groundwater with more highly saline water from deeper aquifers.
4. If saline groundwater is used as a coal carrier, the corrosivity of the slurry would increase and corrosion inhib-

TABLE 15. CLASSIFICATIONS OF SALINE WATER

Total Dissolved Solids	Concentration, ppm
Fresh	0-1,000
Brackish	1,000-10,000
Salty	10,000-100,000
Brine	>100,000

- itors would be required (antioxidants, or pH adjustment).
5. A hypothetical case is examined where a large coal slurry pipeline ruptures and spills a saline coal slurry. Environmental damage is considered to be of little consequence because of dilution.
 6. Soluble salts in coal are expected to leach into the water carrier whether it is saline or fresh. However, western coals have a negligible chlorine content and are not expected to produce significant leaching.
 7. Saline water would add an evaporated residue to the ash and sludge waste load of the power plant.
 8. In summary, Evans and Rice (10) make the following statement:

...it would appear that one of the chief environmental impacts of coal slurry pipeline operations-consumptive use of potable water in the western coal resource areas - can be substantially reduced by the use of saline groundwater without introducing any significant problems along the pipeline.

Recent studies by Sanguanruang and Moore (71,72) examined the water quality aspects of coal slurries. Two different coals from Wyoming were slurried in three concentrations of distilled water and treated wastewater. After filtration the effluent was tested for water quality changes in a dozen categories. It was concluded that generally the concentration of contaminants in slurry wastewater are increased because of contact with the coal. The major increases were in total dissolved solids, total hardness, sulfate, magnesium, and sodium. Slurry transportation by pipeline is not necessarily a beneficial coal-washing technique. The increases in contaminants in the slurry water are measured in mg/l and are still insignificant compared to the total weight of contaminants. For example, sulfate and organic sulfur in the slurry water are increased, but overall sulfur reduction in the coal is negligible.

In a telecon with Prof. Moore, he expressed the opinion that a coal slurry would probably not behave totally like an activated charcoal filter because some of the contaminants were a result of physical processes and others a result of chemical processes. Though saline water was not tested, the high level of chlorides in some coals combined with high chloride levels in some water carriers (e.g.) seawater contains ~ 35,000 mg/l chloride leads Prof. Moore to speculate that seawater or saline water with high chloride levels would not be acceptable as slurry water pipelined to power plants.

Since the coal would not be dewatered completely, a high chloride content would result in wet scrubber corrosion. Thermal drying could reduce the moisture content substantially but would not remove the chloride. The new environmental regulation re-

quiring wet scrubbers for flue gas desulfurization increases the potential of chloride corrosion. While corrosion is a common problem in power plants, it is unlikely that the corrosion level caused by coal high in chlorides could be tolerated.

Treated wastewater would not be expected to be high in chlorides if the raw water source were not high in chlorides. Treated wastewaters with a high chloride content, although less frequently encountered, would not be desirable.

SECTION 4

DEWATERING

Dewatering is the final operation in a slurry pipeline system. Before any environmental effects of dewatering can be discussed, the dewatering activities should be examined.

Conventional components of coal slurry dewatering systems include the following:

1. Centrifugation
 - a) solid bowl
 - b) screen bowl
2. Vacuum Filtration
 - a) disc
 - b) horizontal belt
3. Thermal Drying
 - a) flash dryer
 - b) fluid bed dryer
 - c) rotary dryer

These components cannot be discussed in detail here because of their wide range of application. However, components which have been used in the terminals of two long-distance coal slurry pipelines will be discussed. These pipelines are the Cadiz-Eastlake line in Ohio (no longer operating) and the operating Black Mesa line in Arizona. The major operating characteristics of these two pipelines and their respective dewatering systems are listed in Table 16.

Because the Cadiz-Eastlake line was the first coal slurry pipeline, its dewatering system (Figure 7) contained a number of components found to be unnecessary after its initial startup in 1957. Though not shown in the flow diagram, the slurry was discharged into thickeners prior to entering the vacuum disc filters. The thickeners proved to be unnecessary.

The dewatering facility at the Eastlake Power Plant comprised three major components, each with its own special operational difficulty. The first was the vacuum disc filter. Initial wear problems necessitated the replacing of the plastic woven

TABLE 16: CHARACTERISTICS OF CADIZ-EASTLAKE PIPELINE IN OHIO
AND BLACK MESA PIPELINE IN ARIZONA*

<u>Characteristic</u>	<u>Cadiz-Eastlake</u> <u>(1957-1963)</u>	<u>Black Mesa</u> <u>(1970—)</u>
Length	174 km	439 km
Diameter	254 mm	457 mm
Throughput (MTPY)	1.36	4.36
Coal moisture(%)	2.0	10.74
Coal sp.gravity	1.35 ₂	1.45
Coal heat value	12,000 BTU/lb.	12,300 BTU/lb.
Percent solids by weight	50 to 60	46 to 48
Particle size	43 μ m (20%)	43 μ m (20%)
Capacity range	118 to 182 TPH	509 to 600 TPH
Main separator	Disc filters	Solid bowl centrifuges
Clariflocculator use	Yes	Yes
Desired boiler coal feed moisture	9%	25%
Actual coal feed moisture(%)	7%	32%
Thermal heating method	Flash dryers burning coal	Primary air and gas burners
Slurry heating	No	Yes

*Source: References 17, 73, and 74.

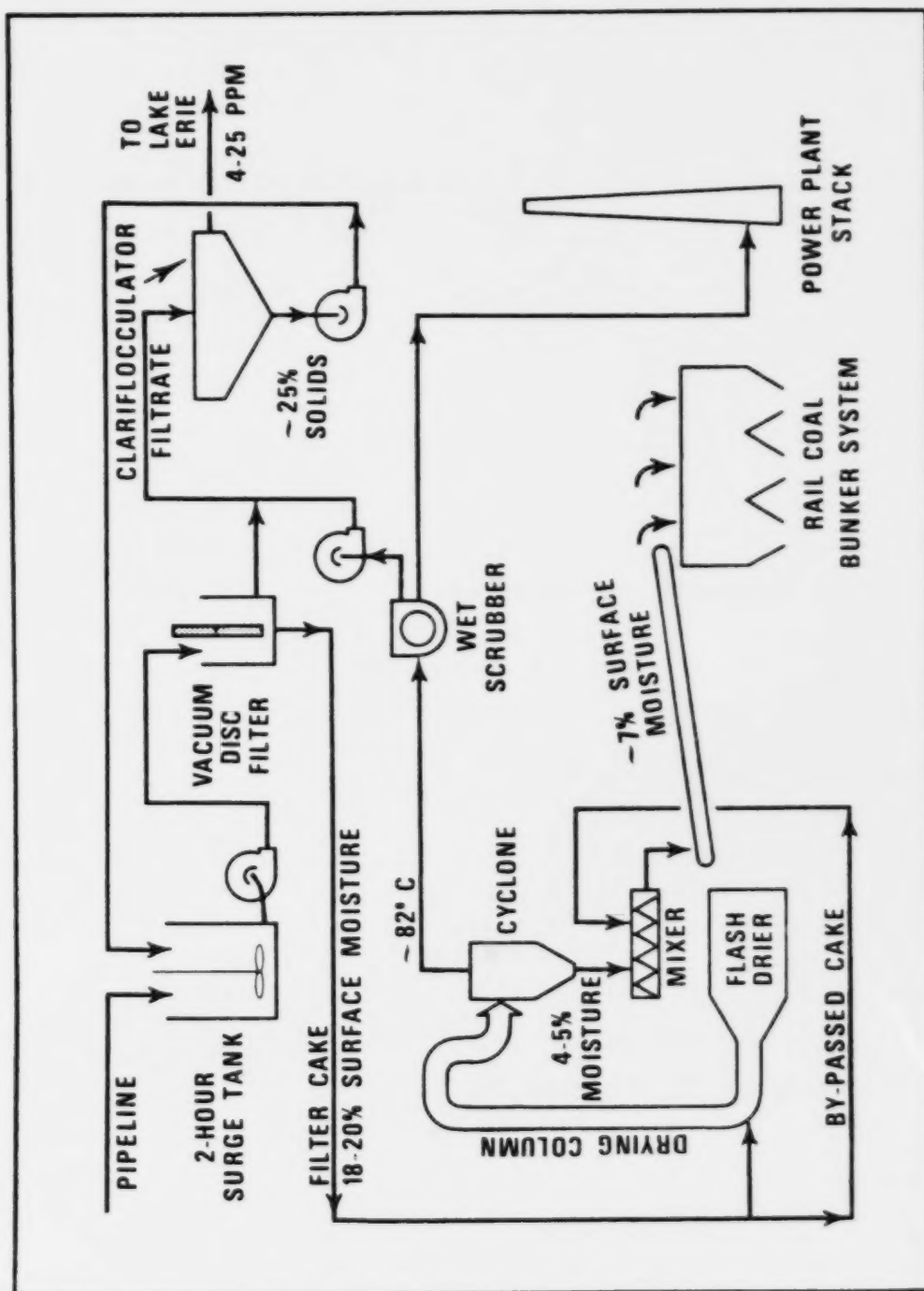


Figure 7. Flow diagram: Eastlake pipeline coal utilization (74)

cloth with a wear-resistant stainless steel cloth. The second was the flash drier with its associated drying column cyclone and wet scrubber. The flash drier was operated on pulverized coal and consumed approximately 3% of the coal entering the plant (74). The problem initially with the flash drier was that it produced a product that was too dry, and dust became a problem. This difficulty was alleviated by re-routing an appropriate amount of the drying column feed around the flash drying unit and mixing it with the flash drier product for a resultant moisture product of 7% (Figure 7).

The hot (82°C) gases at the tops of the cyclones were scrubbed to remove the fine coal dust. The moisture-laden gas (dust removed) from the scrubbers proved to be a problem. Moisture condensed as the air passed through the colder discharge ducts on its way to the plant stack. As a result, highly acidic water had to be removed continually from the stack base and treated in a clariflocculator (73).

The last component was the clariflocculator, which received fine coal particles from two sources--the water from the vacuum disc filter and the water from the wet scrubber that treated the hot cyclone gases. These products passed through the clariflocculators where the underflow (at 25% solids) fed the initial surge tank and the overflow (at 4 to 25 ppm) discharged into Lake Erie (74). A number of chemicals were added to maintain the effluent quality within prescribed limits. The first was a caustic to maintain an effluent pH of 7.0. The second was a coagulant introduced into the clariflocculator to assist in separating the fine coal and water. Finally, additives were used to maintain an oxygen inhibitor concentration of less than 1 ppm in the effluent.

It has been noted (73) that the effluent from the clariflocculator had fewer suspended solids than the water taken from Lake Erie for steam condensing purposes. At that time, the lake water was rarely less than 60 ppm suspended solids while the clariflocculator effluent ranged from 4 to 25 ppm. An estimated 5 pounds of coal were lost per hour.

The suspended solids effluent quality is impressive. However the amount of chemical additives contained in the effluent must also be considered--the chemical flocculant, the additive to counter the oxygen inhibitor, and the caustic.

Dust is a problem in any coal-fired power plant, and the Eastlake plant was no exception. Dauber and Gill (73) summarize the dust problems in the plant and their solutions below:

The foregoing problems and their solutions cover the major ones occurring in the coal preparation plant. However, the unusually fine hot (82°C) dry coal (5%

moisture) intensified and created problems as it was being transferred by the conventional belt conveyors to the coal bunkers in the main unit generating plant. The leakage at the skirts of the conveyor chutes became intolerable, requiring extra men to clean up the coal dropping from the belts. Dust created at transfer points of the belt became a matter of concern. Further, when the weather became cold, the warm, moist vapor from the coal created a very dense fog. This condensed on the cold conveyor gallery surfaces and building ceilings. The drippings from the surfaces were like rain. Where it was below freezing, ice collected.

Installing seals rather than conventional skirts on the ends of the coal belt transfer chutes effectively decreased the leakage. Also, raising the moisture from 5 to 9% significantly reduced the dust problems. A collecting system to remove the dust and moisture-laden air at the belt transfer points is being installed. The space above the coal bunkers will be heated. These steps, it is expected, will give satisfactory conditions along the conveyor.

The second example of a dewatering system, the Black Mesa pipeline, avoided some of the problems encountered at the Eastlake plant but at the same time generated new ones unique to Black Mesa. The Black Mesa dewatering plant flow sheet is illustrated in Figure 8.

The Black Mesa dewatering system contains four major components: the heat exchangers for raising the slurry temperature, the solid bowl centrifuges, the pulverizers where the coal is crushed and mixed with drying air, and the clariflocculators.

The solid bowl centrifuge is the workhorse of this system, just as the disc filter was in the Eastlake plant. The centrifuge rotates at approximately 1000 rpm, and slurry feed enters in the center. The coal is moved away from the water by a screw conveyor that is rotating about 11.5 rpm faster than the bowl.

Wear becomes a large problem in the centrifuges. The screw flights and centrifuge linings wore out too quickly for dewatering to be economical. These problems were solved by installing ceramic tiles on the screw flights and using a centrifuge liner of stainless steel. Average centrifuge life then increased from approximately 1,500 hours to 10,000 hours but is now limited by the life of the cone liners (17,9). The life of the screw flights is approximately double the life of the liners so the flights are refurbished about every second centrifuge overhaul. Materials and labor costs for centrifuge maintenance in 1976 averaged 10¢ per tonne of coal cake (75). There are no adverse en-

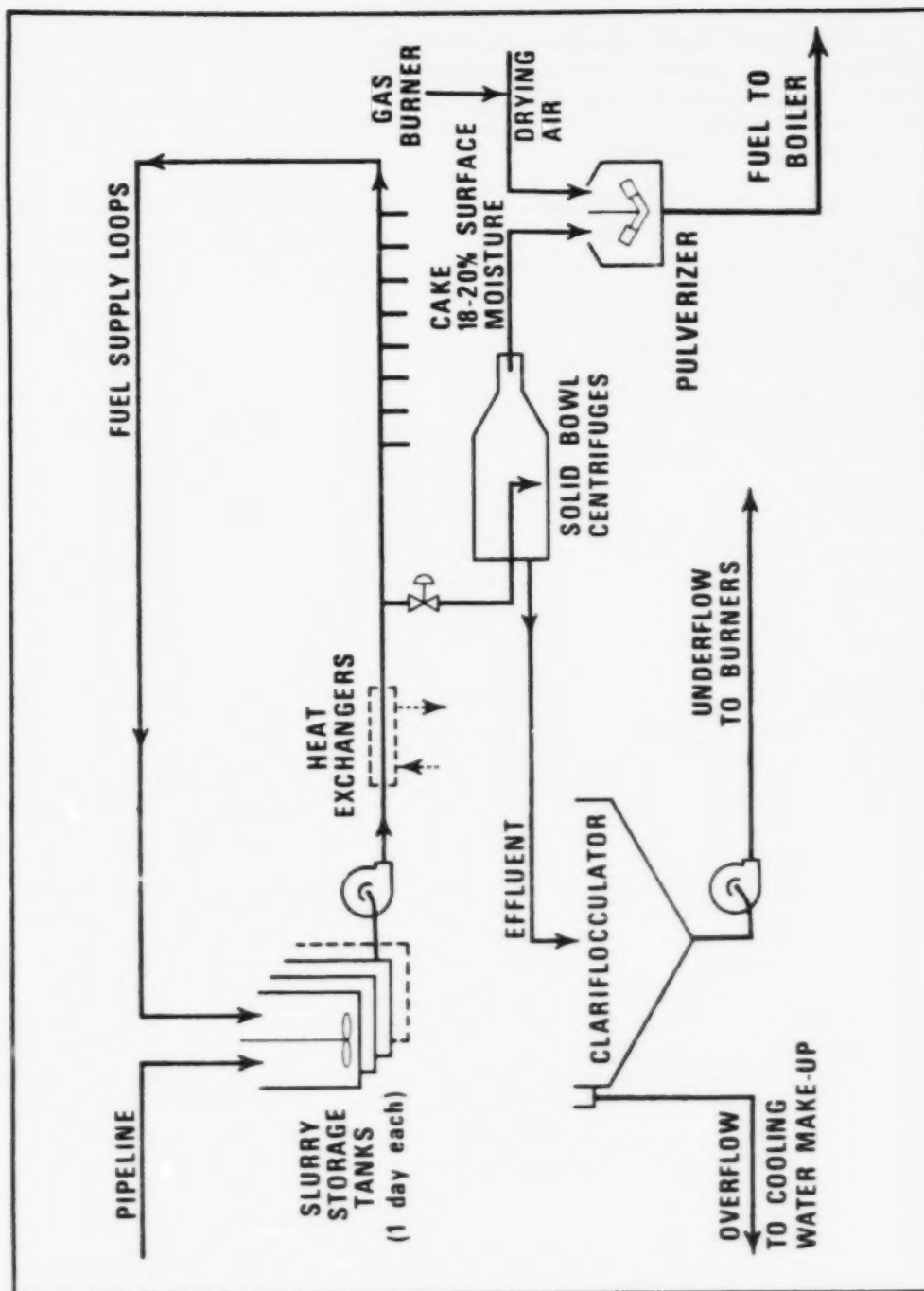


Figure 8. Flow diagram Mohave pipeline coal utilization (74).

vironmental considerations associated with the operation of the centrifuges.

Two centrifuges feed every pulverizer. As the coal is moved to and through the pulverizer, primary air at 400°C dries the coal before it is classified and tangentially injected into the boiler furnace. Dust could be a problem here but the entire pulverizer system is enclosed.

The effluent from the centrifuges is sent to the clariflocculators where chemicals similar to those used in the Eastlake plant are added to aid in coagulation. The cost of the chemical additives can be quite substantial. In 1975, for example, chemical costs amounted to \$5.60 per dry tonne of coal produced from the clariflocculators (17). This cost has subsequently been greatly reduced to \$1.10 per dry tonne in 1976 after a switch in chemicals and manufacturers (9). Most of this cost goes to maintenance of the dewatering equipment. Clariflocculator chemicals now comprise only 5 to 10% of the \$1.10.

The overflow from the clariflocculators is used as cooling tower makeup water, resulting in zero effluent discharge while the underflow is injected into the furnace. This injection can only be performed when the furnace is operating between loads of 600 to 740 Megawatts; outside this range severe operating difficulties, such as slagging or over-pressures, occur (17).

By February 1976 some 400,000 tonnes of clariflocculator underflow had been produced and not burned for various reasons. The underflow had to be stored in a total wastewater pond 14 hectares in area and 3 meters deep. Research is being performed presently to determine alternate methods for handling this product effectively.

Slurry heating has proven to be highly desirable in meeting the requirement of 25% moisture in the coal feed to the furnace. The heat exchangers currently have the capability of raising the slurry temperature to 88°C, but the optimum appears to be 82°C (17). The Mohave operation is now heating slurry to only 82°C because of limitations in the centrifuge driveshafts. It seems that the drier coal exerts a greater load on the driveshaft than that for which it was designed, and a large number of driveshaft failures result when slurry temperature is raised above 82°C. With extra-heavy-duty driveshafts and heating to 88°C it is expected that the additional heating of primary air with gas burners will no longer be necessary, and the recycling of the clariflocculator underflow back to the centrifuges can be accomplished according to the original design plan.

Foreign practice, particularly in the United Kingdom and Japan, makes use of an oil additive to coal slurry to encourage agglomeration of 2 to 5 mm balls which can be removed by screening (76).

The Mohave plant does not have the dust problems that the Eastlake plant experiences because of the higher moisture content of Black Mesa coal. However, coal is stockpiled at the Mohave plant, and this action has the potential for dust control problems. The stockpiles at the Mohave plant utilize chemical sealing sprays to handle the dust problem, as noted by Snoek, et al. (74):

Here (at Mohave) a pile about 200 meters long, 50 meters wide and 6 meters high of dewatered coal was stored under adverse conditions of high winds and low humidity. The pile at its maximum contained about 85,000 tonnes of coal. The dust problem was controlled very nicely by spraying the pile with a sealing compound.

There was little spontaneous combustion problem with this pile, less than might be expected with rail coal. One would expect less spontaneous combustion problems because the fine coal restricts air circulation through the pile.

Another problem confronting the Mohave plant is the processing of outcrop coal. When a slurry containing coal with lower pH, lower heat value, higher ash, and higher inherent moisture is directed to the centrifuges, difficulties such as overloading occur. Difficulties also occur in the clariflocculators when processing this coal. As it has been noted (17), "The amount of chemicals required to treat this centrate (of outcrop coal) increases in magnitude by five, and at times no amount of chemicals can treat it."

Although each facility has or had its own particular operational difficulties, the one thing that both the Cadiz and Black Mesa pipeline dewatering facilities had in common was the use of clariflocculators and the addition of chemicals to aid in coal-water separation.

Although Black Mesa does not discharge any effluent into a local water course, it does use large areas for wastewater evaporation. A possible impact, although slight, might be the attraction of migrating water fowl to these ponds. Chemicals used in the clariflocculation process for corrosion inhibition of pH adjustment could prove to be harmful to these birds. Therefore, even though the Mohave plant approximates zero discharge, its semi-effluent from clariflocculators could have an environmental impact. A way to minimize the impact would be to choose chemicals carefully to aid in coagulation and corrosion inhibition or to neutralize the chemicals after the job is finished.

Similarly, the chemicals used in conjunction with clarifloculator operation in the Eastlake plant--the oxygen inhibitor, the caustic, and the flocculant--produced an impressive solids

effluent quality; on the other hand, the cost to other water quality variables must be simultaneously considered. While improving one particular water quality variable, other variables could be degraded. Careful choice of chemical additives must be made to minimize any adverse environmental impacts.

There is an alternative to slurry dewatering that should be mentioned at this point. The alternative is the direct burning of a coal slurry. This option was attempted in 1961 when the Werner Power Station of the Jersey Central Power and Light Company at South Amboy, New Jersey, successfully fired 10,000 tonnes of coal in concentrated slurry form in one month (74). Cyclone furnaces, originally designed for poor grades of coal and high variations in coal feed moisture, were instrumental in making the test program a success.

The coal slurry used came either directly from the terminus of the Cadiz-Eastlake coal slurry pipeline or from the Georgetown Preparation Plant of Consolodation Coal Company, which supplied the coal for the Cadiz pipeline. The average concentration of the slurry burned was 67% coal by weight.

As expected, the furnace operated at a slightly lower efficiency (about 4.5%) while burning slurry when compared to regular plant feed. This was because of the extra moisture and an increased exit gas temperature (74). Nevertheless, the test was considered an unqualified success.

The drawbacks were not immediately discernable, but because of the higher combustion temperatures, high concentrations of oxides of nitrogen were produced in the stack gas. The concentrations exceed today's Federal EPA emission standards, and presently there is no adequate flue gas scrubbing technology available for NO_x removal (74).

One aspect of dewatering concerns the possible discharge of effluent that is contaminated with corrosion inhibitors. While most slurry pipelines do or will terminate at a zero discharge power plant, there may be situations where a coal slurry pipeline terminates at a barge or rail facility (Figure 9). Unless an alternate use were found or the water carrier were somehow returned to the origin of the slurry pipeline, the water would obviously have to be discharged into a local water course. This action necessitates treatment, but the kind and amount of treatment depends on the chemicals utilized.

Previous discussion dealt primarily with chemicals involved in coal separation, but consideration must be given to corrosion inhibitors as well. Jacques and Neil (77) list the various corrosion inhibitors currently available with a relative rating of effectiveness as well as environmental desirability.

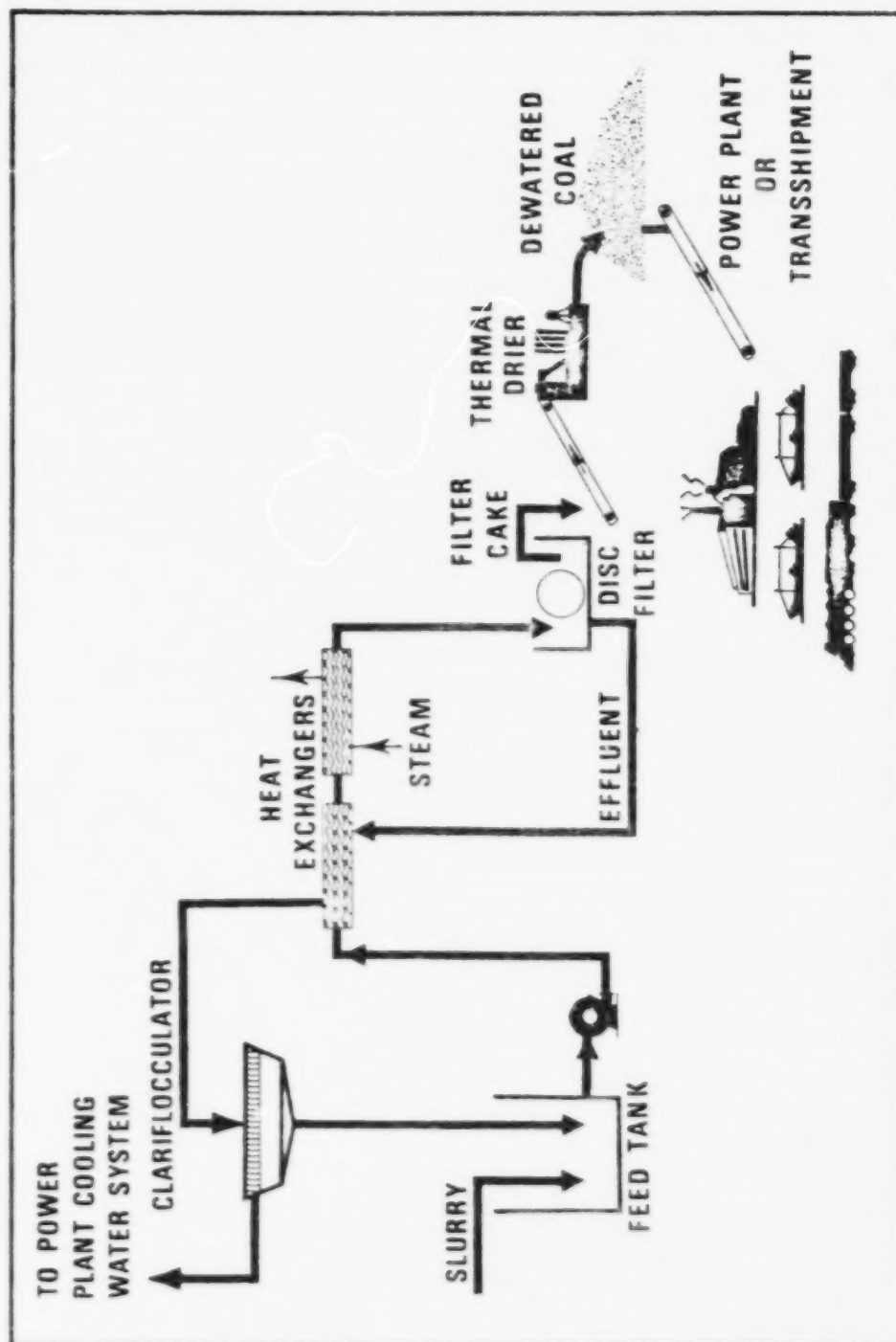


Figure 9. Pipeline coal dewatering flow diagram (74).

Hexavalent chromium is an excellent corrosion inhibitor but has poor environmental acceptability. EPA standards require less than 0.05 ppm concentrations in plant effluents. There are some electrochemical devices commercially available that can remove chromium for an operating cost of from 1.3 to 2.6 cents (1975) per cubic meter treated. One manufacturer has a large device (with a capacity of 4.5 cubic meters per minute) capable of such a process (78). The Black Mesa pipeline, if it were to discharge all of its water resulting from its clariflocculator operation and if the water contained chromium, would require two such devices, but they would not be working at full capacity. At the rate of 3.06 cubic meters per minute per power plant unit--and at a top cost of 2.6 cents per cubic meter treated--the Black Mesa facility would expend approximately \$234 on operating costs per day to treat for a theoretical concentration of chromium in a theoretical effluent discharge.

In conclusion, it appears that most of the physical aspects of coal water separation have no adverse environmental impacts. However, chemicals involved in dewatering processes do have possible adverse environmental impacts. Careful selection of chemicals must be made to minimize those impacts.

SECTION 5

PIPELINE CORRIDOR SELECTION AND CONSTRUCTION

Corridor selection is made according to the same criteria used in designing the entire pipeline system--economics, engineering, and environmental impact (the three E's).

Corridor selection is an important aspect of any pipeline system because it influences the design, operation, and longevity of the pipeline. Because the cost of steel pipe constitutes a substantial portion of the total cost of a long-distance pipeline, economics dictates that the route be as short as possible. Hence, the first step in route selection is to draw a straight line from source to terminal. A right-of-way is selected, usually 25m wide for construction and maintenance purposes, as well as for a balanced design, possibly up to a kilometer in width for a "corridor of influence." The latter width is for studying environmental impacts. External constraints will eventually flex the straight line route into a final design route.

The constraints are basically societal and engineering constraints. The latter are usually natural obstacles which can be accommodated because pipelines can go around, over, under, or possibly pass through obstacles when proper protective measures are used. Engineering constraints may be accommodated using the following rules:

1. Avoid excessive trenching in rock to reduce excavation costs.
2. Slurry pipelines may require a grade limitation (e.g., coal slurry pipelines usually do not exceed grades of 15 to 20%, either up or down).
3. Circumvent large bodies of water such as lakes or wide river crossings.
4. Where water crossings cannot be avoided, utilize existing railroad or highway bridge supports whenever possible.
5. Water crossings also can be made by
 - a) floating the pipe on the water surface when the water level is devoid of surface fluctuations and waves (e.g., a small sheltered lake without navigation),
 - b) laying the pipe on the bottom of the river or lake where stable bottoms exist (e.g., regulated rivers), or

- c) burying the pipe in a trench in the river or lake bottom when the bottom shifts because of wave forces or stream currents.
- 6. Rivers with steep banks can be crossed by suspension bridges built exclusively to support a fully-loaded pipeline subjected to dynamic stresses. These types of bridges are simple in design and more aesthetically pleasing with their long, graceful appearance.

Societal constraints, on the other hand, tend to be more complex. Basically, they occur wherever potential environmental impacts may be encountered, such as in National forests, in State parks, on Indian reservations, in wildlife habitats, on historical or archeological sites, and in high-density population areas.

Since the right-of-way for a pipeline corridor is narrow (about 25m), construction may be permitted to pass through an environmentally sensitive area. Disruption is greatest during the construction stage. If its impact can be tolerated for the relatively short construction period, then the impact is almost nonexistent during the operation of the pipeline. This will be discussed in more detail later.

Numerous techniques are available for pipeline route planning, but probably the most versatile is that technique which uses a digital computer to evaluate the three E's for grid cells along a proposed pipeline route (79). An initial route or alternate routes are selected, avoiding natural obstacles discussed previously as engineering constraints. A convenient grid system is selected with natural and cultural variables plotted by cell along the proposed route. The corridor of influence is approximately a kilometer wide for convenience but can be easily changed to adapt to any particular project requirements.

According to Stastny's (80) method, the individual cells are evaluated on eight weighted criteria: 1) vegetation, 2) topography, 3) water and wet land, 4) transportation, 5) population density, 6) land use constraints, 7) future land use, and 8) soil or agricultural capabilities. All criteria are assigned a value from 0 to 10; the higher the value, the higher the impact (and hence the less desirable for a pipeline). The data necessary to assess the cells come from recent aerial photos, USGS topographic maps, county master plans, historical societies, and any other available sources.

The data usually can be plotted in any of the following ways: 1) as a percentage of cell coverage, 2) as the number of times occurring in a cell, and 3) as the maximum or minimum values in a cell. For example, vegetation could be measured as a percentage of cell coverage, local roadways could be assessed as mileage and class occurring in a cell, and elevation could be assessed according to maxima, minima, and volume above sea level.

In effect, a land resource-use inventory is established.

When all the data are plotted, a computer draws a family of maps or overlays, one for each of the eight criteria, and corridors are selected for each overlay on a minimum impact basis. The next step is subjective: a multidisciplinary team assigns each map with a particular weight. Using the weighted data, the computer produces a final composite map, and a final pipeline corridor of least environmental impact is chosen. Only after a field reconnaissance is performed and the findings incorporated into the data can the final pipeline route be selected. The flexibility of this approach allows the addition or removal of constraints, or the variation of cell size to reflect the accuracy desired.

The goals of this approach or any pipeline route selection technique are the following (80):

1. To minimize damage to natural systems
2. To minimize conflict with existing land uses
3. To minimize conflict with proposed land uses
4. To minimize conflict with culturally significant features
5. To minimize total investment
6. To maximize potential right-of-way sharing

The final goal--maximizing potential right-of-way sharing--of any pipeline route selection deserves additional comment. Buck (44) expanded on this subject well:

A coal slurry line can utilize right-of-way corridors. Perhaps an abandoned pipeline can be refurbished to transport coal. The most obvious common corridor use, exploited by a slurry line, is the electrical transmission line which leads directly to the generator, the consumer of the coal. A coal slurry line built in an existing corridor can share the maintenance, the surveillance and even the emergency facilities and communications networks of the utilities already in that corridor.

An area already developed and maintained rarely suffers excessive environmental damage from the addition of a slurry line...The common corridor usage usually allows a ready acceptance of the coal slurry line by the public and agencies alike.

An example of such utilization of an existing right-of-way occurred in the construction of the Bruce Mansfield Power Station Project (81). The project utilized an old, abandoned railroad right-of-way on property procured from the bankrupt Penn Central Railroad to locate a slurry pipeline for scrubber sludge treated with a stabilizer. The line is approximately 11 km long.

The concept of utility corridors is not new. Telephone and power lines are carried on common poles in utility easements in suburban areas. Many large cities are underlain with utility tunnels carrying telephone, electric, gas, steam, sewer, and water systems. Europe has had extensive overland utility corridors for decades simply through necessity--because of the scarcity of land.

CONSTRUCTION

The construction of coal slurry pipelines does not differ appreciably from the construction of oil and gas pipelines. Oil and gas, though, are more hazardous than coal-water slurries. By following the same construction practices for oil and gas, coal slurry pipelines automatically meet the environmental and safety requirements for oil and gas pipelines. The API Bulletin on Construction Practices for Oil and Products Pipelines contains more than 75 pages pertaining to methods of construction and specifications. These are not reproduced in detail here but major techniques can be highlighted. Minimum safety standards are given in the Code of Federal Regulations, 49-Transportation, Parts 100 to 199, Revised, 1973, by the Office of Pipeline Safety, U.S. Department of Transportation. Assuming that all the necessary right-of-way permits are procured legally, there are eight activities that may potentially produce an environmental impact in the construction stage. They are the following: 1) clearing and grading, 2) ditching (including river, highway, and railroad crossings), 3) storage, haulage, and stringing of pipe, 4) welding the pipe, 5) coating and wrapping the pipe, 6) backfilling the trench, 7) cleaning up, and 8) testing the system.

During the construction of a coal slurry pipeline, activities 1 through 7 can be accomplished (according to the API bulletin) in approximately 10 to 14 days at any given point along the pipeline route when conditions are ideal (82). However, according to other sources (83), "It takes about four days for a pipeline construction spread to move past a specific point; four days from the time the ground is open to the time it is filled in." Figure 10 illustrates these various activities (although they are never spaced that close). Pipeline progress is usually 3 km per day with crews spread out over 30 km. Each activity does have the potential of producing an environmental impact and is considered individually.

Clearing and grading is the first aspect of construction that strips topsoil and lowers the grade to the desirable design level. It should be noted that minor work on fences and route surveying precede the actual clearing and grading and these activities pose a very slight environmental impact potential. Clearing and grading constitute short-lived activities. If they are not executed with the proper care, pollution of local water-

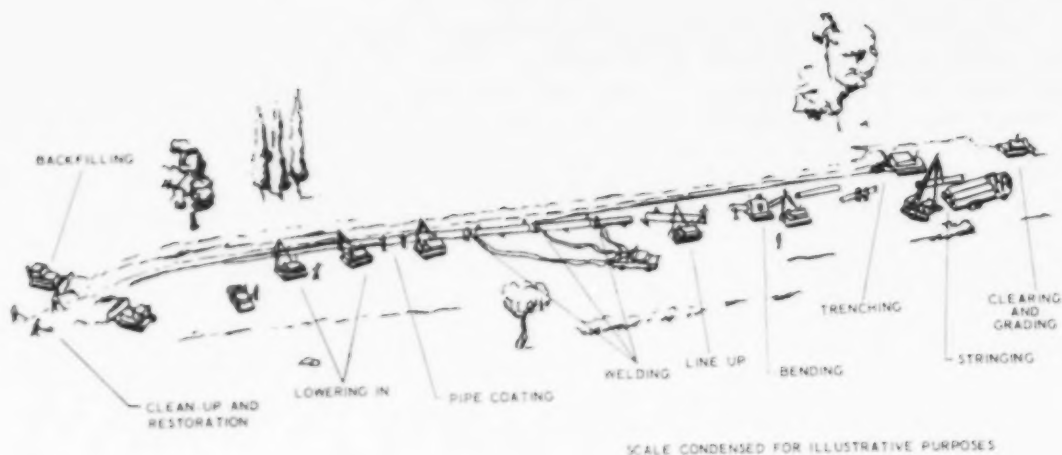


Figure 10. Typical pipeline construction spread.(40)

sheds can occur. If a severe rainstorm should occur while clearing or grading and the usual safeguards are not taken, the runoff could pollute a local stream with suspended solids. The result of such an occurrence would have to be assessed on a case-by-case basis. However, it should be noted that this impact possibility is common in the construction of almost any overland travelway, whether highway, canal, railroad, or pipeline. The solution to the problem is also as common: small catch basins or ponds can collect the excessive runoff and allow the suspended solids to settle out before the water is discharged into the watershed.

The principal hazard with ditching, likewise, is pollution from runoff. In extreme cases, wind erosion of the excavated material could become a problem. Fugitive dust is another problem common to most construction projects. The solutions include spraying of chemical soil stabilizers or simply using water trucks to wet the exposed material. Although the pipeline route reconnaissance team may detect archeological evidence, ditching as well as clearing and grading offers the highest potential for archeological discovery. If a competent archeologist is not on site, it is recommended that one be on call just in case items of historical or prehistoric interest are uncovered.

River and lake crossings have already been discussed (see page 59).

Highway and railroad crossings must also be done with care

to maintain the integrity of the sub-structure of the travelway. If improperly executed, a crossing could transfer loads from the roadbed to the pipeline. Repeated loading could lead to external stress on the pipeline and possible structural failure. Probably the best method for crossing railways and highways is tunneling under the crossing. Usually a tunnel can be augered and encased by a rigid pipe through which the slurry pipeline is passed and supported. This method of crossing is least disruptive and relatively inexpensive, and it usually ensures minimum stress distribution on the slurry pipeline. It should be noted that highway and railroad crossings are nothing new to pipeline-laying crews, and every engineering safeguard available is employed.

The storing, hauling, and stringing of pipe does not constitute much impact because these activities occur adjacent to the trench. Storage of pipe at centrally located facilities may conflict with land uses, but at the rate pipeline construction progresses the storage site would be temporary.

Oil and gas pipeline codes presently are suitable for coal slurry pipelines (84) although the slurry pipeline industry is in the early stages of establishing a code committee. If welding is performed strictly according to code, the only impact from welding activities would be the discarding of expended electrodes. Care taken by the welders would eliminate this litter. It should be noted that some pipeline companies employ automatic welding machines. These machines probably use electrodes more efficiently and completely, and their use would result in even less impact because of welding activities. While the possibility of inadequate welds is present, any such flaws in the system would be detected when the pipeline is tested by X-rays for structural integrity.

Coating and wrapping of pipe according to established codes would also offer insignificant impacts. Again, litter--consisting of unused material or packaging material--would be a minor nuisance. The biggest potential impact that might develop would occur if the coating and wrapping were not done properly and corrosion occurred as a result. Corrosion would cause the pipe to become reduced in thickness, subjecting the pipe to possible leakage in time (or even rupture if the allowable design pressure were exceeded). However, the coating and wrapping is performed according to code and the possibility for corrosion is remote.

The tradition of good workmanship in pipeline design and installation is evident from the age of many water, oil and gas pipelines, some still operating after more than 100 years. Long-distance slurry pipelines are installed with a life expectancy of 20 to 50 years, depending on the abrasivity of the solids. Coal slurry pipelines are expected to last more than 35 years.

The backfilling of the trench must be done with care. Soil

should be replaced to duplicate the original conditions. All subsurface soil should be replaced first, finishing with the layer of topsoil. (The two are easily segregated in the clearing and grading stage). Rock which might damage the wrapping and coating of the pipe should not be placed in contact with the pipe. Compacting and final grading to the rough original contour is normally performed.

In some cases, revegetation to the original growth is necessary while in other instances it is not. For example, when revegetating an agricultural area, the revegetative species should closely approximate, if not duplicate, the original ones so as not to be in conflict with the intended land use. On the other hand, consider the case of the pipeline route located in the middle of a forest. Revegetation practice might be guided by the possibility that the pipeline right-of-way could serve as a firebreak. From all viewpoints that is exactly what the completed pipeline right-of-way would appear to be, a firebreak. In addition to the dual use of the pipeline right-of-way is the obvious potential for large tree roots damaging the pipeline, and the pipeline route--for the sake of safety--should, therefore, be devoid of large trees.

The final construction activity is testing. There are many different methods of testing a pipeline, including x-raying the welds, pressurizing the line with air or water, or utilizing ultra-sonics to actually listen for leaks (85). Cracks as small as 20% of the material thickness can be located with 90% probability and 95% confidence. This can be compared with locating leaks of 70% of the thickness when conventional radiographic techniques are used. The increased sensitivity is obtained by improving several image characteristics (86). Hydrostatic testing is done before the trench is backfilled. Dynamic testing of a slurry pipeline occurs after completion of construction and will be examined shortly.

Thus, while it appears that there are construction activities capable of producing environmental damage, they tend to be short-lived and of a minor consequence.

SECTION 6

OPERATION AND MAINTENANCE

Operation and maintenance of a slurry pipeline extend to the entire system and involve attention to slurry preparation, pipeline transportation, and slurry separation. Even though there may be separate ownership of each subsystem, successful operation requires coordination and cooperation from each part. Operation and maintenance are required for the following:

1. The water supply source and its collection system
2. The water pump stations
3. The water supply pipeline
4. Coal source and its mining system
5. Coal washing facility
6. Slurry preparation facility
7. Slurry pipeline
8. Slurry pump station
9. Power supply system
10. Slurry dewatering facility
11. Overall physical plant upkeep

Operation and maintenance of the first three items are conventional whether the water supply comes from groundwater or surface water reservoirs. Coal mining and cleaning are also conventional, whatever the transportation mode. Similarly, items 9 and 11 are conventional and require no elaboration. Slurry dewatering was discussed in an earlier section.

The slurry preparation facility is essentially conventional but with a few exceptions. Because of the limited flexibility in the optimum design of a long-distance slurry pipeline, the size distribution of the coal cannot be varied widely without a concomitant change in power requirements. The operation of the preparation plant must be rigidly controlled to prevent excessive generation of fines, which are difficult to dewater at the pipeline terminal, and to prevent excessive generation of coarse coal particles, which accelerate pipewall wear and require more power for pipeline transportation. Control is achieved by screening the coal, recirculating over-size coal back to the crushers and grinders, and preparing the slurry to the appropriate solids concentration in holding tanks prior to pipelining. When unconventional slurries are to be experimented with, a test loop is some-

times connected to the holding tanks to develop pipe flow information on these slurries before they are switched over to the main pipeline for long distance transport.

Experience at Black Mesa (17) has shown that outcrop coal with higher ash and water contents is difficult to dewater and burn. These problems can be mollified, not at the slurry preparation plant but at the coal mine where blending of outcrop coal with higher quality coal can be achieved. A better long-term solution might be to install a washing plant facility to reduce the ash content and, possibly, the sulfur. This would leave some of the waste products at the mine for easy disposal and would reduce the amount of waste products and emissions at the power plant.

Operation and maintenance of the pipeline and pumping stations would appear to offer the greatest danger of environmental impact and pollution. Pipeline shutdown and utilization of the dump ponds at pump stations would appear to be the most probable undesirable event that might occur.

PIPELINE SHUTDOWN

As shown in Section 2, external causes are responsible for most pipeline accidents. When no external causes produce a failure, three internal causes might develop pipeline shutdown: a leak, a rupture, or a cessation of flow due to a solids plug.

In the late stages of construction, structural leaks are located during hydrostatic testing. According to the ANSI B31.4 code (86), a new petroleum pipeline must be subjected to a hydrostatic pressure level of 1.25 times its maximum operating pressure for a period of 8 hours. Though the code is not mandatory for slurry pipelines, both the Consolidation Coal and Black Mesa pipelines met this code requirement comfortably (87).

After a period of operation (as long as several decades), corrosion leaks can develop from improper pipe protection (i.e., coatings, wrappings, and cathodic protection).

Pipe protection is required externally from corrosion and freezing and internally from erosion and corrosion.

External Protection

There are several corrosion protection methods for steel pipes (88). In order of increasing effectiveness, they are ranked as follows:

1. Use heavy wall thickness. This is expensive and only prolongs the rate of deterioration.

2. Improved backfill. Granular clean sand is recommended but is still prone to infiltration of leached salts.
3. Loose polyethylene sheets can be used (and have been used since 1965). These 8-mil thick unbonded sheets which encase the pipeline are forbidden by code on gas pipelines but have been used on slurry pipelines.
4. Cement mortar coating is better than the above but still vulnerable to chlorides and stray electrical currents.
5. Use insulating coatings, the most popular of which is hot applied coal tar enamel. This has been used since 1854 in England and for over 100 years in the United States. Coating is usually preceded by chlorinated rubber primer and followed by wrapping of fiberglass paper or asbestos felt.
6. Cathodic protection is considered the superior form of external protection when used with one of the above protective measures. Long underground pipelines can deteriorate electrolytically because of differences in electrical potential. Induced currents from power lines, dissimilar metals, and soil composition cause an electrolytic action in which the pipe is consumed. Cathodic protection involves the reversal of the natural tendency for the uncontrolled discharge of current from anode areas on the exterior surface of buried ferrous metal pipelines. To reverse this circuit, external sacrificial anodes (usually magnesium or zinc) are buried in the soil adjacent to the pipeline and connected electrically to the pipe. The size, number, and spacing of anodes required is dependent upon the particular installation and environment. The external anodes result in the pipeline becoming a cathode, with no external corrosion taking place on the pipeline. Cathodic protection of an uncoated pipe, however, is considered to be uneconomical.
7. Normally the pipeline is buried below the frost line. Where it must be exposed to freezing temperatures, heat trace cables and insulation are used.

Internal Protection

Coal slurries transported in long-distance pipelines are so fine that erosion of the pipe wall is minor. The erosion is due primarily to the ash in the coal. Because the coal is ground finely, the transport velocities may be kept low ($<2\text{m/s}$), thereby reducing erosive wear. Corrosive wear is due to the oxygen in the water and is thought to be of the same order of magnitude as erosive wear. The two wearing phenomena act in concert as a synergistic system, resulting in greater total wear than the sum of the two components. Corrosion builds up an oxide scale on the pipe wall, which is abraded by the coarser coal particles. Nevertheless, the total wear rate is much less than with most mineral slurries.

Internal protection can be achieved several ways:

1. Increase wall thickness. This is an expensive method, one used at Black Mesa.
2. Use oxygen inhibitors. This method was tried on Consolidation Coal pipeline. Various cost and environmental disadvantages exist.
3. Line the pipe interior. A method of the future, this appears to be promising when use is made of interior coatings rather than linings.
4. Remove the oxygen. Another method of the future, this also may be expensive.
5. A combination of the above or partial use of the above methods may be used.

Jacques and Neil (89) examined the above schemes and concluded that long-distance coal slurry pipelines would probably benefit from a lining of the pipe for the first segment followed by increased wall thickness for the remainder of the distance. The oxygen in the water would be consumed by the coal usually within the first 80 km, thereby reducing the need for a high corrosion allowance in pipewall thickness. For example, Black Mesa was designed for a corrosion allowance of 0.3mm/year and so far is on schedule. When the dissolved oxygen level is below 1/2ppm, the corrosion rate decreases markedly and the corrosion allowance can be reduced to 0.075mm/year.

Internal coatings and linings which show promise are polyurethanes and epoxy-polyamids. Because the pipe would be factory-coated, part of the coating would be burned off as each joint was field-welded. The interior coating would have to be repaired in the field. Although there are presently no means to detect "holidays" in coating, it may not be crucial to the protection of the pipe if a few pinholes occurred in the coating. Another possible major advantage of coatings might be a reduction in wall friction if the coating provides an interior finish smoother than steel. The disadvantage of coatings is that they might deteriorate in time from abrasive wear, particularly on the invert of the pipe. Tests are required to evaluate coatings.

Such technical developments have this aim in common--to produce a more economical and safer pipeline without the use of oxygen corrosion inhibitors, some of which are environmentally unacceptable.

Leaks and Ruptures

A pipeline leak by definition is a small discharge through a pinhole, a loose pipe connection, a weakened weld, or a valve on a branch pipe which lacks total closure. Light aircraft fly pipeline routes on a 2-week basis, flying as low as 30 meters, but a pipeline leak may not be evident from an aerial surveillance. Depending on the size of the leak and upon the operator's experience, a reduction in flow at the terminal may be shown by a mag-

netic flow-meter when compared to a higher flowmeter reading at the head end of the pipeline.

It is unwise to assume that a pinhole leak will plug itself with fine solids. Experience has shown that the water escapes, resulting in an increase in solids concentration. This in turn increases the energy requirement for pipeline transportation. When a leak is suspected but cannot be detected physically, the slurry should be replaced by clear water and a leak detector installed. An ultrasonic leak detector (84) with an electronic recording instrument is placed in the flow (much like a scraper pig). It measures the noise generated by flow of a liquid through a small hole and can locate a leak within 100 meters.

A rupture is more serious than a leak because it is usually instantaneous, leaving little time to take corrective action. Generally, ruptures are caused by pressure transients and occur at the weakest stress area in the pipeline (usually in thin-wall or eroded pipe). Pressure transients are caused by sudden (improper) pump start-up and shutdown (power failures) and fast valve stroking. Pressure transients can be calculated quite accurately for single-phase liquids. The transients in slurries are usually moderated by the presence of solids (90) and are, therefore, more difficult to evaluate. Protective devices in the form of surge dampeners and pressure relief valves (rupture discs) are installed in a location where the pressure waves can cause excessive pressures in the pipeline and where they are accessible for maintenance. Should they fail to respond properly, the pipeline can rupture. Ruptures are usually a meter or two in length and several centimeters wide. The reduction in flow and pressure is picked up essentially at the speed of sound by instrumentation at the pump stations. The pumps are stopped and block valves close automatically. If no block valves are present, the ruptured line drains all continuously higher pipeline elevations. As the slurry drains through the rupture, the propagation of the slurry will be influenced by the topography of the land at the rupture point. For example, steep gradients will produce a long, narrow plume of slurry which could extend a considerable distance; a flat gradient will produce a localized, deeper puddle. Unless the coal is highly acidic, which is unlikely, it is expected that the water would infiltrate the soil quickly and evaporate without undue harm to the environment. Ultimately, the dried fine coal might be blown by the winds. Since coal is essentially inert, adverse impact on the environment is not anticipated, at least not more than from spillage when a unit train derailment occurs. Needless to say, the safety hazards from ruptures of gas and petroleum products pipelines are much greater than those of coal pipelines.

EMERGENCY STORAGE

Most long-distance slurry pipelines utilize emergency storage. Three types are possible, depending on location of the pipeline. Water ponds may be located at high points of a pipeline for back-flushing the system in the event of an unscheduled shutdown. Water released by gravity flows back to each pump station to a dump pond, removing most of the solids in the pipeline on its journey. This type of storage is not used frequently because of the difficulty in obtaining water at high elevations.

Commonly, pump stations have both a water storage pond and a slurry dump area. The two storage areas are constructed at the same time if the land is available. In the event of an unscheduled shutdown, where start-up is difficult because of a high solids concentration, each segment of the pipeline upstream of a dump pond can be pumped into the dump pond by the previous booster station. The advantage is increased flexibility in the operation of the pipeline. Since a long-distance slurry pipeline attains its economic advantages in high-volume throughput and high use factors, the role of emergency storage is to minimize shutdown time and lost capacity. The slurry storage pond is a last resort, to be used only when a high concentration slurry cannot be pumped through to the power plant. The goal is to avoid solids dumping because it represents lost revenue from lost product and downtime. Usually the pump stations are somewhat remote, and reclamation of the coal is difficult. It is too costly to re-slurry the coal and put it back into the pipeline. Slurry dumping is too infrequent to warrant the cost of a separate slurry pump circuit for the return of dumped solids to the pipeline.

Pipeline operators prefer to keep the solids in the pipeline. When pumping difficulties are encountered, operators prefer to add dilution water. If water can be added at downstream pump stations, the preparation plant gains time to adjust the slurry properties while the pipeline is still operating. Without this flexibility, the pipeline operation would take longer to correct if water is available only at the main pump station.

Pipeline designers want to omit dump areas and water reservoirs at the booster pump stations in future pipelines since these are to some extent, redundant. The operators, on the other hand, see the emergency ponds as a strong advantage in maintaining high use factors for the pipeline and in preventing coal losses by dumping. Black Mesa experience (91) has shown that little excess water is pumped to the power plant during start-ups. There is a tendency to transfer water from one station pond to the next station pond downstream during this operation.

Slurry dump ponds are customarily designed for two dumpings of the pipeline volume upstream and downstream of the dump area. A dyked impoundment area is usually adequate. A deep pond is re-

quired to reduce evaporation if there is a desire to maintain the coal in slurry form; a wide, shallow pond is required if dry coal is desirable. If the coal dries out and is subject to wind losses, a binder can be sprayed on the coal such as is done to hopper cars.

The third location for emergency storage is at the lower elevations in the pipeline between pump stations. Automatic dump valves and an impoundment area are necessary. Normally this type of emergency dumping is reserved for steeply inclined pipelines that exceed the suggested maximum slopes (15 to 20%) for slurry pipelines. A pipe is installed at steep angles because of topographic constraints. Steep pipes, however, produce two major disadvantages in slurry operation: slack flow and potential plugging during shutdown. Slack flow means that a pipe is flowing partially full at a higher velocity than normal and under a negative pressure. These two effects can cause localized invert wear from erosion and can promote cavitation. The higher velocity accelerates erosion by imparting higher kinetic energy to the solids. Cavitation results from low pressures (at the vapor pressure of the liquid), producing bubbles which move downstream to a higher pressure area and implode, creating local structural damage (pitting) to the pipe. After shutdown the solids in the steep pipe slide downward and block the entire cross section of the pipe. Such a pipe is difficult to unplug with a pump. Virtually all unplugging techniques require fluidization of the settled solids before flow can be initiated. This is readily accomplished when a liquid layer exists above the settled solids. A slow start-up will move the water first, eventually entraining the solids until full suspension is achieved. If the entire pipe cross section is blocked with settled solids, the water will compact the plug in an attempt to clear it. Unless the plug can be blown free into a nearby dump pond, it may be almost impossible to break it by pump pressure alone.

While fast-settling slurries would have to be dumped automatically upon pump shutdown, slow-settling slurries may provide time (up to several days) to take corrective action to restart the pumps after unplanned shutdowns. Again, operator preference is to use the ponds only as a last resort. Their choice is to batch high-concentration slurries with slugs of water to reduce the pressure drop and to keep the coal in the pipeline.

The environmental effects of dumping into ponds would be minimal. The dump ponds can be lined to prevent seepage of coal or water from the slurry into the local groundwater supply. There are a number of ways, then, to empty the dump ponds. The coal could be dredged and hauled away in trucks, the coal could be returned to the slurry pipeline during a water run (an unlikely situation), or the coal could be left in place by letting the water evaporate. The last action could result in an adverse impact if the dried coal is exposed to the elements. Wind might

suspend the coal dust, blowing it over the local landscape. Another impact involves the possible attraction of migratory or indigenous waterfowl to the dump ponds. The toxicity and pH variations of these ponds would be harmful to the birds. These impacts, blowing of coal dust and attraction of water fowl, can be minimized by utilizing a chemical treatment which would detoxify the slurry and, at the same time, stabilize it against the elements. The dump ponds and the rest of the pump station also can be an impact simply by occupying land that could have a different use. As slurry pipeline experience is broadened, it may become possible to eliminate or reduce dump ponds and thereby alleviate this impact somewhat.

Pump stations need a source of power. Stations are usually in remote locations and are electrically powered. The power lines running to the pump stations tend to be a lightning target and, perhaps more important in any consideration of environmental impact, present a visual impact.

Another area of impact associated with slurry pipelines concerns the population increase necessary to provide the manpower to operate it. Unlike other transportation modes, coal slurry pipelines are not labor intensive. With automation one man can operate the Black Mesa pipeline--although the normal number is 53 men, with 38 at the preparation plant. The proposed ETSI line will require 335 men while a railroad hauling the same amount of coal per annum would require 2570 men. Compared with the railroad alternative, the impact associated with the increase in an area's population because of the operation of a pipeline is minimal when viewed from the standpoint of increased housing and land use.

The operation of a slurry pipeline may also have beneficial impacts in air quality at the power plant where burning of the slurried coal takes place. Ash removal from the coal before transport is a very attractive possibility from an engineering standpoint. Ash removal reduces energy requirements, coal degradation, and pipeline abrasion. At the same time, ash removal would reduce air and water pollution at the power plant. Ash removal would probably not be implemented if rail transportation were employed.

START-UP PROCEDURES

Dynamic testing of a slurry pipeline occurs after completion of construction and involves a sequence of operations similar to the following:

1. A scraper pig is pushed through the pipeline by compressed air or water to clean out installation debris and to check for any obstacles to flow.

2. Clear water is pumped through the pipeline to check equipment operations and instrumentation (pumps, valves, flowmeters, etc.)
3. Slurries are pumped through in low concentrations, eventually building up to design concentrations, while checking out equipment operations and instrumentation.
4. Shutdowns and startups (both instant and delayed) are practiced to determine any difficulties in operation. At this time dump valves and pressure relief valves are tested. Anti-plugging procedures are examined and modified also. The purpose of this testing stage is to determine the limitations of the pipeline system before it is put into production. Attempts to put the pipeline into immediate production without adequate dynamic testing may lead to serious reductions in use factors at a later date.

PERIODIC TESTING

After some period of operation (usually six months or a year) certain procedures are recommended to evaluate the projected lifespan of the pipeline.

A recent development is the AMF Tubescope (92). It is essentially a smart pig--a metal cylinder driven through the pipe by water pressure. The smart pig has self-contained sensing units which can analyze wall thickness and corrosion throughout the entire length of the pipeline. These data are recorded by a self-contained magnetic tape unit during the inspection, and the tapes are analyzed later in the laboratory. The pipeline is inspected with the Tubescope at or near start-up of the system to establish a base reference and then is run periodically over the life of the project to provide a continuing check on the condition of the pipeline.

Another procedure is to check pipeline wear with spools. These are usually short pipe nipples (~30 cm long) flanged into the pipeline downstream of the first few pump stations where corrosion is apt to be the most extreme. The spools are removed when the line has been drained during a planned shutdown and cleaned, weighed and miked for average and local wear respectively. Corrosion meters, consisting of probes inserted through the pipe-wall, are also used with fair success.

Thompson and Aude (93) have summarized in detail the process, design and construction, and operation of a long-distance slurry pipeline. Their guidelines are reproduced with some minor modifications in Appendix C.

Figures 11, 12, and 13 show the preparation plant facility and the first booster pump station (Gray Mountain) of the Black Mesa coal slurry pipeline. The preparation plant includes the



Figure 11. Black Mesa coal slurry preparation facility.



Figure 12. Aerial view of Gray Mountain pump station.

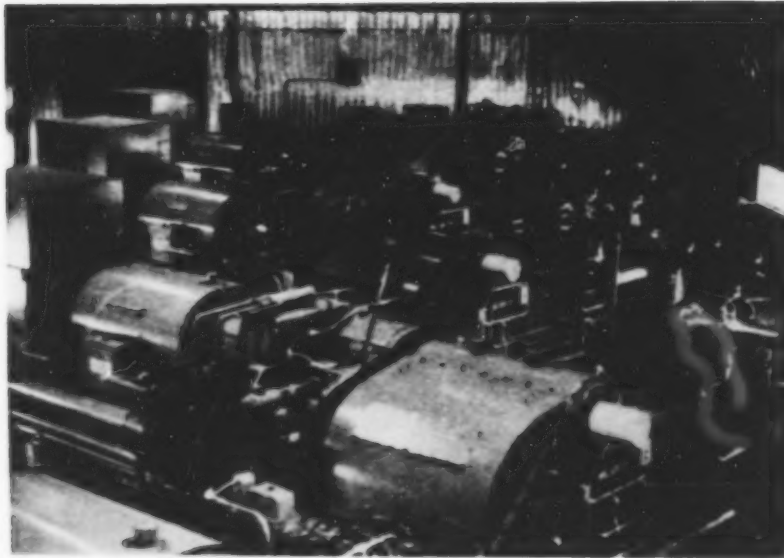


Figure 13. Interior view of Gray Mountain Pump Station

coal storage yard, water storage tank, conveyors, weighing building, crushing and grinding building, slurry mix tanks, and test loop. The Gray Mountain pump station consists of the main pump house, water storage pond for emergency pipeline flushing (the small building is the water pump house), and emergency slurry dump pond. Note the small amount of coal being reclaimed from impoundment area. The interior of the pump house shows a bank of positive displacement piston pumps. When visited in June 1977, the pump station was remarkably clean with no visible signs of coal slurry anywhere.

In summary, the operation and maintenance of a coal slurry pipeline are more complex than, but similar to, the operation of an oil or gas pipeline. Although there are some potential environmental impacts associated with the operation of a coal slurry pipeline, they would be less than the impacts produced by oil and gas pipelines over the last 50 years.

SECTION 7

EPILOGUE

This report has examined the environmental and pollution aspects of coal-water slurry pipelines. These have been found to be minimal and generally not as severe as those produced by alternate energy transportation modes.

Water is truly the Achille's heel of the slurry pipeline system. Without it, present and proposed pipelines cannot exist. If water were readily available as needed, coal slurry pipelines would not be as controversial as they are. The role of water use in the West, is multi-faceted--with legal, political, environmental, and emotional implications. The major point of contention seems to be the allocation of water when it is available. Should it serve agriculture, municipalities, industry, or energy production and transportation?

These restraints have directed consideration of low quality water sources such as deep saline groundwater wells and surface wastewater (industrial and municipal sewage). Until these alternate water sources become prohibitively expensive to exploit, they will be investigated as potential water supplies.

In the future, what potential improvements may be forthcoming to reduce the amount of water required for a coal slurry pipeline? The first step, perhaps, would be to increase the solids concentration beyond 50% by weight. In terms of specific power (kw-hr/tonne-km) the lowest value optimizes operating costs, provided a minimum operating velocity is maintained to prevent solids deposition. If the concentration is increased, the headloss requirement to overcome pipewall friction increases also. For a given screen size distribution there is an optimum solids concentration. As discussed by the author elsewhere (94), there is in fact, an optimum coal particle size distribution for the entire slurry pipeline system. However, there is no strong evidence that suggests much higher solids concentrations are achievable for coal-water slurries to provide economical long-distance transportation by pipeline. The hydrophobic tendencies of most coals are believed to be at least partially responsible for this.

The next logical step is to alter the slurry structure arti-

ficially with chemicals, causing an effective decrease in slurry viscosity for the same solids concentration and size distribution, or, conversely, permitting an increase in solids concentration for the same pressure drop. A few additives have been found to reduce slightly the viscosity of coal-water slurries, but none has been found cost effective to date. Work continues in this area but success appears limited.

There are several advantages to be gained by increasing solids concentration. The quantity of water is reduced, leading to higher solids concentrations and higher headlosses for pipeline transport but reducing dewatering costs. In addition, the efficiency of the power plant is increased from the reduced moisture content of the coal. The savings accrued by the reduced water must, of course, be included in the economic balance.

The ultimate goal of coal slurry pipeline transportation should be direct combustion at the power plant. It seems folly to add water to coal for no other purpose but transportation and then to remove the same water from the coal to permit combustion. Most coals are hydrophobic and do not mix well with water. Once mixed and pipelined, complete separation is impractical with existing technology. There are enough fines ($<50\mu\text{m}$) and the specific gravity of the coal is close enough to that of water so that conventional dewatering techniques must include costly thermal drying to remove enough water to allow efficient combustion.

As mentioned previously, direct combustion was tried in 1961 using cyclone burners at the Jersey Central Power and Light Company (95). Slurry was obtained from the Cadiz pipeline. The burns were considered successful, but apparently the stack emissions would not meet present day air pollution standards, specifically nitrous oxide levels.

Perhaps if water becomes too scarce and/or costly, the technology of direct combustion will be re-examined. A compromise of first stage rough dewatering with a higher pipelined solids concentration or a coarser size distribution may be possible.

ENERGY SLURRIES OF THE FUTURE

If direct combustion looks desirable and feasible in the intermediate future, the logical extension of this thinking for the long term is to consider a total energy slurry-coal delivered in a hydrocarbon liquid carrier. The carrier could be crude oil, synthetic crude oil (Syncrude), or a member of the alcohol family such as methanol.

Crude oil is unlikely to be available where coal is mined. It would have to be pipelined to the coal source and mixed there for slurry transport to market. Possible customers would be

utility plants, which are presently burning oil and which must convert to coal as oil supplies dwindle or become excessively expensive. Retrofitting of oil burners to coal-oil slurry burners may be justifiable economically instead of total conversion to coal. Alaskan crude oil and Montana coal or Dakota lignite might be potential candidates for future consideration. Some proprietary research is investigating the separation of coal and oil at the terminus of a pipeline, but previous research (96) suggests this may be expensive. Therefore, direct combustion of the total slurry may be the best approach.

The concept of the creation of a liquid hydrocarbon carrier from coal at the mine site is appealing, provided more water is not used in the process than that required by a coal-water slurry pipeline. The economics of liquifaction are poorly understood pending further research. Consequently, the economics of producing a liquid hydrocarbon, such as synthetic oil or methanol, are vague. However, some preliminary work which appears encouraging has been done:

1. Wentworth Bros. proposes to build a lignite-to-methanol conversion plant in North Dakota. The methanol would be pipelined to the Lakehead for shipment via the Great Lakes or rail spur for eventual use as a turbine fuel to drive generators (97).
2. L. Keller, president of Methacoal Corp. of Dallas, Texas, has patented a process in which methanol is made from coal and used as a carrier for coal in pipeline transportation. The coal and methanol may be separated for various uses or burned directly in a boiler. Methacoal is claimed to be hydraulically stable (no solids deposition, even for laminar flow, inexpensive to produce, non-consuming of water, and more economical than low-sulfur crude oil (40)).
3. Banks and Horton (98) have examined efficiency improvements in pipeline transportation systems and have recommended research and development for eight systems, two of which involve methanol-coal slurries.

Transport Energy Ratio

When pipeline transportation of fossil fuels is involved, the transport energy ratio may be defined as the ratio of energy required for transport to the total usable energy delivered. In terms of energy slurries this can be simplified to the ratio of energy requirement for overcoming pipewall frictional resistance to the calorific content of the slurry transported. Thus, a common assumption inferred is that pump motor efficiencies, elevation differences, and minor losses are essentially constant regardless of the slurry and are therefore ignored. Another assumption is that the market use in each case will be combustion of fossil-derived fuels in thermal electric generating stations. While the water that is separated from a coal-water slurry is used for

cooling purposes, it has no input energy value for combustion. The transport energy ratio is

$$\frac{\text{specific power} \times \text{throughput of combustibles}}{\text{calorific content delivered}}$$

$$\frac{\text{kw-hr}}{\text{tonne-km}} \times \frac{\text{tonnes}}{\text{hr}} \times \frac{\text{hr}}{\text{Joules}} = \frac{\text{kw-hr}}{\text{Joule-km}}$$

where tonnes refers to the mass of combustible solids and liquids. The specific power is the power required to overcome pipe-wall resistance in delivering one tonne of combustibles per hour a distance of one kilometer. The smaller the transport energy ratio, the more efficient the energy slurry for pipeline transportation.

Table 17 compares the transport energy ratios (kw-hr/Joule-km) for three energy slurries tested by the author. Water is also included to round out the comparison because it has zero energy efficiency. The slurries tested were a Black Mesa type of coal (similar in size distribution to that of Black Mesa) in water and a Utah coal both in No. 2 fuel oil and in commercially available methanol. The coal properties varied and are listed in the table. The chief difference was particle size distribution. The Utah coal was significantly finer than the Black Mesa type of coal. The power requirements for pipeline transport were estimated from rheological data taken in the Colorado School of Mines Rheology Lab. Scale-up headloss equations verified from field operations with numerous mineral slurries were applied to the energy slurries.

Operating conditions at the Black Mesa coal slurry pipeline were used as the standard. Table 17 estimates the transport energy ratios for the energy slurries if transported under similar flow conditions in the Black Mesa pipeline.

Several interesting observations can be made from the comparison. The range of transport energy ratios varied from about one-half to in excess of two. While a minimum ratio is desirable, it is obvious from the data that this is achieved by increasing the weight concentration of the solid or liquid phase with the higher calorific content. Because the alternate fuels (oil and alcohol) are more valuable than coal, it is apparent that the choice of energy slurry for transport must be optimized in conjunction with its preparation. The availability or processing of the higher-priced carrier liquid will be critical. If the oil or alcohol is converted directly from coal, it is probable that processing economics will dictate a high coal/low liquid carrier mixture.

For combustion purposes no dewatering costs will be incurred, so effectively this cost can be transferred to the head end of

TABLE 17. COMPARISON OF ENERGY SLURRIES*

Slurry	C _w , % [†]	Sp.grav. mix	Tonnes/hr [‡] dry coal	Tonnes/hr liquid	Tonnes/hr total	kPa [§] km	Specific power kw-hr/ [#] tonne-km	Energy ratio kw-hr/ 10 ⁹ Joule-km ^{**}
Water	0	1.000	0	981.8	981.8	46.525	0.0129	
Black Mesa coal in water	46.9	1.172	539.5	611.4	1150.9	71.791	0.0364	2.140
Utah coal in methan- ol	63.7 54.6	1.105 1.046	692.0 561.0	394.7 467.0	1086.7 1028.0	174.279 114.018	0.0439 0.0304	1.469 1.109
Utah coal in #2 oil	45.0 55.0 65.0	1.027 1.083 1.144	453.8 584.5 730.2	554.7 478.3 393.2	1008.5 1062.8 1123.4	71.649 104.254 226.996	0.0195 0.0269 0.0553	0.472 0.647 1.442

*Flow conditions: Velocity=1.75m/s; I.D.=446.1mm; pipe roughness=0.046mm; temperature=30C; elevation gradients and pump-motor efficiencies excluded.

Assumed calorific content: Black Mesa type coal-28.6; Methanol-19.7
(10⁶Joules/kg) Utah coal-27.9 ; #2 Oil-44.7

Weighted mean particle size: Black Mesa type coal: ; Utah coal:
0.308mm

Specific gravity=1.456 ; specific gravity=1.429

[†]C_w = concentration of dry solids by weight
Liquid specific gravity: Methanol=0.791; #2 Oil=0.835

[‡]tonnes/hr = metric tonnes per hour transported

[§]kPa/km = pressure drop to overcome pipewall friction in kiloPascals/km

[#]kw-hr/tonne-km = specific power for pipeline transport in kw per tonne per hour of combustibles per km of horizontal distance.

^{**}kw-hr/10⁹Joule-km = energy transport ratio = specific power required to overcome pipewall resistance in delivering 10⁹ Joules a distance of 1 km.

the pipeline for grinding the coal to a finer size. Since pulverization of coal to about 85% minus 75 microns is necessary for power plant combustion, this grinding cost is not attributable to pipeline transportation. The finely ground coal allows high stable slurry concentrations to be produced, thus minimizing the amount of carrier liquid. Also, the affinity that coal has for hydrocarbon liquids enables easier slurry mixing, avoiding the often-encountered hydrophobic tendencies of coal in water.

The disadvantage of this process, is that if the coal is ground so finely, the slurry becomes paste-like with a high viscosity and high energy requirement for pipelining. However, the elimination of dewatering costs means that additional costs can be absorbed by increased pipeline transportation costs.

Preliminary work suggests a strong potential for energy slurries to become an alternate power plant fuel of the future. If burned directly, this fuel, besides being higher in calorific value, would probably ameliorate the materials handling problems associated with railroad-delivered or coal-water slurry coal. It is strongly recommended that coal-liquid hydrocarbon slurries be researched at the preparation stage, pipeline transportation stage, and combustion stage to evaluate their economics.

Because energy slurries are combustible, their transportation by pipeline would probably present the same environmental and pollution consequences as oil pipelines.

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APPENDIX A

MAJOR PIPELINE INSTALLATIONS

SUMMARY OF MAJOR PIPELINE INSTALLATIONS

SLURRY CODE	LOCATION	OWNER	SPECIFIC GRAV. OF SOLIDS	DIAMETER IN MM	CONC WT.	VEL M/S	L KM	CAPACITY TONNES PER YEAR	INITIAL OPERATION YEAR	PUMP TYPE	PUMP /STA	TOTAL PUMPS	REF.
ASH-T	SUNBURY PA	PA-POWER & LIGHT	2.25	254.0	10.0	4.39	2.408	---	1956	CSE	-	5	1
ASH-T	SAFE HARBOR PA	PA-POWER & LIGHT	2.4	152.4	17.0	1.62	1.372	---	1953	CSE	-	6	1
CO-C	BLACK MESA, AZ-USA	CONSOLIDATION	---	254	---	---	---	1.18	1957	DAPI	2	9	-
CO-C	CADIZ, OH USA	HANNA COAL CO	1.4	457.2	---	---	---	4.53	1970	DAPI	2	9	-
CO-C	CHESNICK, PA, USA	PA-POWER & LIGHT	1.85	273.0	50.0	1.52	173.8	---	1957	DAPI	2	13	1
CO-C	POLAND	HANNA COAL CO	1.5	323.8	---	---	---	---	1953	C	-	6	-
CO-C			---	152.4	52.5	2.44	0.792	---	1957	C	-	1	-
CO-C			---	254.0	---	---	---	---	---	---	-	-	-
CO-O	ROBINSON RUN MINE WVA, USA	CONSOLIDATED COAL CO	---	254.0	38.0	4.27	.925	60.0	---	C	-	2	-
CO-O	LOVERIDGE, W. VIRGINIA	USA CONSOLIDATED COAL CO	---	504.8	---	---	---	---	1978	C	-	-	-
CU-C	KBI TURKEY		---	127.0	---	---	---	0.91	---	---	-	-	-
CU-C	BOUGAINVILLE		---	152.4	---	---	---	0.91	1972	VPL	3	2	-
CU-C	ARBITER PLANT, USA		---	101.6	---	---	---	0.18	1974	---	-	-	-
CU-C	WEST IRAN		---	101.6	---	---	---	0.27	1972	VPL	3	2	-
CU-C	PINTO VALLEY, USA		---	101.6	---	---	---	0.36	1974	PL	3	2	-
CU-C	ELSDO-LIANTA, CHILE	ANACONDA	---	152.4	---	---	---	727.3*	1959	---	-	-	-
CU-C	HAYDEN, AZ, USA	KENNECOTT COPPER CO	4.2	152.4	26.0	1.22	0.853	---	1958	CSE	-	4	1
CU-C	IDSA, FREPORT-WIRAN		---	101.6	---	---	---	831.8-	1973	---	-	-	-
CU-T	JAPAN		---	304.8	---	---	---	0.5	1968	DAPI	2	3	-
CU-T	WHITE PINE, MI, USA	WHITE PINE COPPER	2.7	587.3	17.5	3.22	1.897	---	1953	C	-	4	1
CU-T	BUTTE, MT, USA	ANACONDA	1.2	508.0	---	---	---	25454.5*PP	---	CSE	-	7	-
CU-T	W. VIRGINIA		1.4	101.6	---	---	---	---	1957	C	-	4	-
CU-T	W. VIRGINIA		1.4	102.1	---	---	---	---	1957	C	-	4	-
CU-T	CANADA	U.S. BORAX	2.6	127.0	---	---	---	---	1957	C	-	4	-
CU-T	MONTANA, USA	ANACONDA	---	508.0	---	---	---	18181.8*	1964	C	-	3	-
FE-C	WALPPI(LAND)		---	203.2	---	---	---	0.91	1971	C	-	8	3
FE-C	CHONGIN, N. KOREA		---	304.8	---	---	---	0.91	1971	C	-	6	3
FE-C	SAVAGE RIVER, TASMANIA		5.0	228.6	---	---	---	98.17	1975	---	-	4	-
FE-C	PENA, COLORADO-MEXICO		5.0	203.2	---	---	---	85.30	1967	PL	3	4	4
FE-C	SIERRA GRANDE, AGTA		5.0	203.2	---	---	---	46.28	1974	C	-	2	4
FE-C	LAS TRUCHAS, MEXICO		5.0	203.2	---	---	---	27.36	1974	PL	3	3	4
FE-C	SAMARCO, BRAZIL		5.0	508.0	---	---	---	402.3	1975	PL	3	3	4
FE-C	CANADA		---	---	---	---	---	27.36	1977	PL	3	14	4
FE-C			---	---	---	---	---	2.1E+06	---	---	-	-	-

SUMMARY OF MAJOR PIPELINE INSTALLATIONS

SLURRY CODE	LOCATION	OWNER	SPECIFIC GRAV. OF SOLIDS	DIAMETER IN	CONC WT.	VEL M/S	L KM	CAPACITY TONNES PER YEAR	INITIAL OPERATION TYPE	PUMP /STA	TOTAL PUMPS	REF.
FE-C	LABRADOR-PT. MARMITE, CAN		---	203.2	---	---	---	10.9	1974	----	-	-
FE-T	HUNTER PLANT	M.A. HANNA	3.2	406.4	16.0	2.92	5.364	---	1955	C	-	8
FE-T	STAR LAKE, NY, USA	LAUGHLIN STEEL	2.7	298.5	20.0	3.66	1.524	---	1957	C	-	14
FE-T	CALUMET, MN, USA	LAUGHLIN STEEL	2.8	406.4	14.8	2.56	2.621	---	1958	C	-	1
FE-T	CANISTEO, MN, USA	CLFVELAND CLIFFS	2.8	457.2	17.5	2.68	0.783	---	1958	C	-	2
FE-T	GRAND RAPIDS, MN, USA	LAUGHLIN STEEL	3.0	609.6	9.5	2.65	1.633	---	1959	C	-	2
FE-T	HIBBING, MN, USA	M.A. HANNA	3.2	488.9	11.0	2.20	3.962	179,199pp	1959	C	-	2
FE-T	MINNESOTA, USA	M.A. HANNA	3.4	406.4	---	---	---	211.8*	1955	C	-	-
FE-T	KEEWATIN, MN, USA	LOMPHOS ORE, LTD	3.0	292.1	---	---	---	5636.4	---	C	-	5
FE-T	SELLWOOD, ONTARIO, CAN	BETHLEHAM CORNMALL	2.8	355.6	4.0	3.20	0.488	---	1957	C	-	6
FE-T	MORGANTOWN, PA, USA	LAUGHLIN STEEL	3.0	254.0	35.0	2.10	2.663	---	1958	C	-	4
FE-T	CALUMET, MN, USA	PHILLIPP CORP.	3.0	609.6	6.0	2.40	1.757	---	1961	CPA	-	2
FE-T	GEORGIA, USA		2.58	203.2	---	---	---	---	1951	C	-	2
GIL-O	UTAH-COLORADO	AMER. GILSONITE CO	1.04	152.4	46.0	1.19	115.9	0.36	1957	PL	-	3
GS-TO	LORRAINE MINE-FREDDIE NORLORRAINE GOLD MINES		2.7	228.6	50.0	1.33	9.449	57272.7+	1963	C	-	8
G-T	CREIGHTON, PA	PITSBG. PLATE GLASS	2.5	101.6	31.0	1.95	1.707	---	1949	C	-	12
HM-C	FLORIDA, USA		3.4	101.6	---	---	---	40.9*	1955	C	-	2
HM-C	AUSTRALIA		1.3	152.4	---	---	---	21.8*	---	----	-	-
HM-C	LAWTEY FL, USA		3.4	101.6	---	---	---	---	1955	C	-	16
KC-O	GEORGIA, USA	PHILLIPP CORP.	2.6	203.2	25.0	1.22	17.70	---	1951	C	-	2
KC-O	GEORGIA, USA	PHILLIPP CORP.	2.6	203.2	33.0	1.22	25.75	---	1959	C	-	3
KC-O	GEORGIA, USA	PHILLIPP CORP.	2.6	304.8	25.0	1.22	8.047	---	1940	C	-	2
LI-O	CALAVERAS		---	177.8	---	---	---	1.4	1971	DAPI	2	-
LI-O	RUGBY, ENGLAND		---	254.0	---	---	---	1.5	1964	DAPI	2	-
LI-O	TRINIDAD		---	203.2	---	---	---	0.5	1959	DAPI	2	-
LI-O	COLUMBIA		---	177.8	---	---	---	0.36	1944	----	-	-

SUMMARY OF MAJOR PIPELINE INSTALLATIONS

SLURRY CODE	LOCATION	OWNER	SPECIFIC GRAV. OF SOLIDS	DIAMETER IN MM	CONC WT.	VEL M/S	L KM	CAPACITY TONNES PER YEAR	INITIAL OPERATION YEAR	PUMP TYPE	PUMP /STA	TOTAL PUMPS	REF.
MIL-T CANADA			---	330.2	---	---	---	9090.9*	---	---	---	---	-
NI-C CANADA			---	203.2	---	---	---	1818.2*	---	---	---	---	-
NI-T WEST MINNESOTA, USA			---	101.6	---	---	---	9.1E-02	1970	---	---	---	-
PHM-C BARTON, FL, USA	ARMOUR AGRICULTURAL CHEMICAL CO. INC		2.75	406.4	25.0	3.658	3.200	---	1955	C	---	4	1
PHM-O FLORIDA, USA	SMITH-DOUGLAS CO. INC		2.7	406.4	25.0	3.658	3.200	---	1960	C	---	4	-
PHM-O NORALYN MINE, FL, USA			2.6	457.2	35.0	5.029	7.62	---	1974	C	---	7	-
PHM-O NORALYN MINE, FL, USA			2.6	508.0	35.0	5.029	7.82	---	1974	C	---	4	2
PHM-O NICHOLS, FL, USA	MOBIL CHEMICAL CO.		2.7	457.2	35.0	3.658	2.743	---	1971	C	---	4	2
PHM-O LEE CREEK, NC, USA	TEXASGULF		2.7	457.2	35.0	3.322	4.420	---	1966	C	---	5	2
PHM-O WHITE SPRINGS, FL, USA	OCCIDENTAL CHEM. CO.		---	508.0	37.0	5.090	5.273	---	1965	C	---	4	2
PHM-O BONNY LAKE MINE	W.R. GRACE		2.6	457.2	32.5	4.572	8.230	---	1946	C	---	10	2
PHM-O FORT MEADE, FL, USA	USS AGRICHEM. CO.		2.65	508.0	30.0	4.724	3.658	---	1968	GIW REPL	3	4	2
PHM-O TAPIRA-UBERABA, BRZL	MIN & CHEM CO.		3.2	244.5	---	---	---	---	1978	C	---	3	-
PHM-O ACHANANORALYN MINE, FL, USA	AMER. CYANAMID CO.		2.7	508.0	40.0	3.658	6.437	---	---	C	---	14	1
PHM-O SYDNEY MINE, FL, USA	SMITH-DOUGLAS CO. INC		2.65	406.4	35.0	3.627	6.096	---	1949	C	---	10	1
PHM-O TENOROC MINE, FL, USA	MONSANTO CHEM. CO.		2.7	406.4	35.0	3.962	3.962	---	1960	C	---	4	1
PHM-O COLUMBIA			---	254.0	25.0	3.719	0.137	---	---	---	---	2	-
PHP-O CONDA, ID, USA	JR. SIMPLOT CO.		2.95	127.0	50.0	5.014	2.295	---	---	C	---	1	2
PHP-O CONDA, ID, USA	JR. SIMPLOT CO.		2.95	203.2	50.0	5.014	2.295	---	---	C	---	1	2
PHP-O SYDNEY MINE, FL, USA	AMER. CYANAMID CO.		2.65	406.4	35.0	3.63	6.096	---	1949	CSE	---	10	1
PHP-O ACHANANORALYN MINE, FL, USA	MIN & CHEM CO.		2.7	508.0	40.0	3.66	6.437	---	---	C	---	14	1
PHO-T MATON, INDIA	HINDUSTAN ZN LTD.		2.8	127.0	40.0	0.488	1.500	---	1976	WSP	---	2	2
PHO-T FLORIDA, USA	CHEMICAL CO.		2.6	406.4	---	---	---	---	1959	C	---	5	-
PHO-T FLORIDA, USA	CHEMICAL CO.		2.6	355.6	---	---	---	---	1952	C	---	7	-
PHO-T	PA. POWER & LIGHT		2.1	254.0	---	---	---	---	1953	C	---	2	-
PHO-T SULLIVAN MONTANA	MERAMEC MINING CO.		4.2	101.6	5.0	---	0.274	---	1964	CRU	---	1	-
PHO-T NICHOLS, FL, USA	VI-CAROL CHEM. CORP.		2.65	355.6	5.0	2.896	7.724	---	1952	C	---	7	1
PHO-T NICHOLS, FL, USA	VI-CAROL CHEM. CORP.		2.65	406.4	5.0	4.237	6.287	---	1958	C	---	5	1
PHO-T CAPE PROV., SAFRICA	CHEMFOS LTD.		2.6	152.4	0.0	1.890	3.060	---	1965	C	---	18	2
PHO-T WHITE SPRINGS, FL, USA	OCCIDENTAL CHEM CO.		2.72	508.0	5.0	5.243	2.967	---	1965	C	---	3	2

SUMMARY OF MAJOR PIPELINE INSTALLATIONS

SLURRY CODE	LOCATION	OWNER	SPECIFIC GRAV. OF SOLIDS	DIAMETER IN MM	CONC WT.	VEL M/S	L KM	CAPACITY TONNFS PER YEAR	INITIAL OPERATION TYPE	PUMP /STA	TOTAL PUMPS REF.
PHO-T	KINGSFORD MN-FL,USA	INT. MIN & CHEM. CO.	2.65	457.2	2.0	4.511	4.267	---	1975 C	-	5 2
PV-C	GMCL,SAFRICA		3.0	127.0	--	---	---	138.8*	----	C	4 -
SI-T	BLACKBIRD,IO,USA	CALERA MINING CO.	2.7	192.4	5.0	1.387	2.262	---	1946 C	-	18 1
SI-T	BRALORNE,BC	BRALORNE PIONEER MI	2.7	76.2	8.0	1.646	1.311	---	1960 C	-	3 1
SI-T	KELLOGG,IO,USA		2.75	127.0	0.0	1.661	2.865	---	1961 C	-	4 1
SI-T	BUNKER HILL,USA		1.46	127.0	--	---	---	38.2*	----	CSE	6 -
SR-T	SUNBRIGHT,VA,USA	MINES IN JAPAN FOOTE MINERAL CO.	1.57 1.8	318.8 101.6	-- 0.0	---	---	36363.6+	1968 DARE 1952 C	-	3 - 4 1
SS-T	THOMPSON,MANITOBA,CAND	INT. NICKEL	3.5	127.0	5.0	3.658	0.3048	---	1959 C	-	4 1
UP-C	UNION S. AFRICA	ANG-TRS-CON-INV CO.	3.0	127.0	1.0	1.372	5.224	---	1963 C	-	8 1
UP-C	DAGGATONTEIN UNION SAFC		3.0	101.6	--	---	2.853	---	1963 C	-	2 1
UP-C	DAGGATONTEIN UNION SAFC		3.0	127.0	--	1.356	2.853	---	1963 C	-	2 1
UR-TO	EAST CHAMP D. OR,RSA	GEN MIN & FINA CORP	2.7	192.4	--	---	---	---	1963 C	-	4 -
UR-TO	BAROSCO,RSA	FREDDIES CONSOL. MI	2.7	192.4	0.0	0.972	19.00	---	1963 PL	-	2 1
UR-TO	FREDDIE-N-S, RSA	FREDDIES CONSOL. MI	2.7	304.7	0.0	1.152	8.138	---	1963 CSE	-	4 1
UR-TO	FREDDIE S-WELSON, RSA	FREDDIES CONSOL. MI	2.7	406.4	0.0	1.207	11.23	---	1963 CSE	-	6 1
UR-TO	PRES. STEYN-WELCOM,RSAPRES	STEYN GOL MIN CO	2.7	228.6	0.0	1.128	6.401	---	1963 C	-	6 1
UR-TO	PRES. BRAND-PRES. STEYNPRES	BRAND GOL MIN CO	2.7	254.0	0.0	1.384	3.673	---	1963 C	-	5 1
UR-TO	PRES. BRAND-SAAIPLAAS,GMCL		2.7	228.6	--	---	---	45300+	1963 CSE	-	5 -
UR-TO	DOORFONTEIN,RSANEW CONSOL.	GO FIELD LTD	2.7	215.9	0.0	0.872	10.67	40000+	1963 CSF	-	6 72
UR-TO	ELLATON-STILFONTEIN,RSAGEN MIN & FINA CORP.		2.7	228.6	0.0	1.027	15.26	2.667+	1963 REPL	-	6 1
UR-TO	S. AFRICA	CO. SUR VAAL REFFS	1.28	---	--	---	---	22727.3+	----	DARE	4 -

APPENDIX B
WATER QUALITY STANDARDS

TABLE B-1. DISSOLVED SOLIDS IN POTABLE WATER(Ref. 60)
(A Classification Based Upon Relative Abundance of Dissolved Solids)

Major constituents(1.0 to 100 ppm):

Sodium	Bicarbonate
Calcium	Sulfate
Magnesium	Chloride

Silica

Secondary constituents(0.01 to 10.0 ppm):

Iron	Carbonate
Strontium	Nitrate
Potassium	Fluoride

Boron

Minor constituents(0.0001 to 0.1 ppm):

Antimony*	Lead
Aluminum	Lithium
Arsenic	Manganese
Barium	Molybdenum
Bromide	Nickel
Cadmium*	Phosphate
Chromium*	Rubidium*
Cobalt	Selenium
Copper	Titanium*
Germanium*	Uranium
Iodide	Vanadium

Zinc

Trace constituents(generally less than 0.001 ppm):

Beryllium	Ruthenium*
Bismuth	Scandium*
Cerium*	Silver
Cesium	Thallium*
Gallium	Thorium*
Gold	Tin
Indium	Tungsten*
Lanthanum	Ytterbium
Niobium*	Yttrium*
Platinum	Zirconium*

Radium

*Elements marked with an asterisk occupy an uncertain position in the list.

TABLE B-2. MAJOR CHEMICAL CONSTITUENTS IN WATER-THEIR SOURCES, CONCENTRATIONS, AND EFFECTS UPON USABILITY(Ref.60)

Constituent	Major Sources	Concentration in natural water	Effect upon usability of water
Silica (SiO ₂)	Feldspars,ferro-magnesium and clay minerals, amorphous silica chert, opal.	Ranges generally from 1.0 to 30 ppm, although as much as 100 ppm is fairly common; as much as 4000 ppm is found in brines.	In the presence of calcium and magnesium, silica forms a scale in boilers and on steam turbines that retards heat; the scale is difficult to remove. Silica may be added to soft water to inhibit corrosion of iron pipes.
Iron (Fe)	1. Natural sources: Igneous rocks: Amphiboles, ferro-magnesium micas, ferrous sulfide(FeS), ferric sulfide or iron pyrite (FeS₂), magnetite(Fe₃O₄). Sandstone rocks: Oxides, carbonates, and sulfides or iron clay minerals. 2. Manmade sources: Well casing, piping, pump parts, storage tanks, and other objects of cast iron and steel which may be in contact with the water. Industrial wastes.	Generally less than 0.50 ppm in fully aerated water. Ground water having a pH less than 8.0 may contain 10 ppm; rarely as much as 50 ppm may occur. Acid water from thermal springs, mine wastes, and industrial wastes may contain more than 6,000 ppm.	More than 0.1 ppm precipitates after exposure to air; causes turbidity, stains plumbing fixtures, laundry and cooking utensils and imparts objectional tastes and colors to foods and drinks. More than 0.2 ppm is objectionable for most industrial uses.

cont'd

TABLE B-2 (continued)

Constituent	Major Sources	Concentration in natural water	Effect upon usability of water
Manganese (Mn)	Manganese in natural water probably comes most often from soils and sediments. Metamorphic and sedimentary rocks and mica biotite and amphibole hornblende minerals also contain large amounts of manganese.	Generally 0.20 ppm or less. Ground water may contain more than 10 ppm. Reservoir water that has "turned over" may contain more than 150 ppm.	More than 0.2 ppm precipitates upon oxidation; causes undesirable tastes, deposits on foods during cooking, stains plumbing fixtures and laundry, and fosters growths in reservoirs, filters, and distribution systems. Most industrial users object to water containing more than 0.2 ppm.
Calcium (Ca)	Amphiboles, feldspars, gypsum, pyroxenes, aragonite, calcite, dolomite, clay minerals.	As much as 600 ppm in some western streams; brines may contain as much as 75,000 ppm.	Calcium and magnesium combine with bicarbonate, carbonate, sulfate and silica to form heat retarding, pipe-clogging scale in boilers and in other heat-exchange equipment. Calcium and magnesium combine with ions of fatty acid in soaps to form soap suds; the more calcium and magnesium, the more soap required to form suds. A high concentration of magnesium has a laxative effect, especially on new users of the supply
Magnesium (Mg)	Amphiboles, olivine, pyroxenes, dolomite, magnesite, clay minerals.	As much as several hundred parts per million in some western streams; ocean water contains more than 1,000 ppm, and brines may contain as much as 57,000 ppm.	
Sodium (Na)	Feldspars (albite); clay minerals, evaporites such as halite (NaCl) and mirabilite.	As much as 1,000 ppm in some western streams, about 10,000 ppm in sea water; about 25,000 ppm in brines.	More than 50ppm sodium and potassium in the presence of suspended matter causes foaming, which accelerates

(cont'd)

TABLE B-2 (continued)

Constituent	Major Sources	Concentration in natural water	Effect upon usability of water
	($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$); industrial wastes.		scale formation and corrosion in boilers. Sodium and potassium carbonate in recirculating cooling water can cause deterioration of wood in cooling towers. More than 65 ppm of sodium can cause problems in ice manufacture.
Potassium (K)	Feldspars (orthoclase and microcline), feldspatoids, some mica, clay minerals.	Generally less than about 10 ppm; as much as 100 ppm in hot springs; as much as 25,000 ppm in brines.	
Carbonate (CO_3)	Limestone, dolomite	Commonly 0 ppm in surface water; commonly less than 10 ppm in ground water. Water high in sodium may contain as much as 50 ppm of carbonate.	Upon heating bicarbonate is changed into steam, carbon dioxide, and carbonate combines with alkaline earths—principally calcium and magnesium—to form a crustlike scale of calcium carbonate that retards flow of heat through pipe walls and restricts flow of fluids in pipes. Water containing large amounts of bicarbonate and alkalinity are undesirable in many industries.
Bicarbonate (HCO_3)	Limestone, dolomite	Commonly less than 500 ppm; may exceed 1,000 ppm in water highly charged with carbon dioxide.	
Sulfate (SO_4)	Oxidation of sulfide ores; gypsum; anhydrite; industrial wastes.	Commonly less than 1,000 ppm except in streams and wells influenced by acid mine drainage. As much as 200,000 ppm in some brines.	Sulfate combines with calcium to form an adherent, heat-retarding scale. More than 250 ppm is objectionable in water in some industries. Water containing about 500 ppm of sulfate tastes

(cont'd)

TABLE B-2 (continued)

Constituent	Major sources	Concentration in natural water	Effect upon usability of water
			bitter; water containing about 1,000 ppm may be cathartic.
Chloride (Cl)	Chief source is sedimentary rock (evaporites): minor sources are igneous rocks. Ocean tides force salty water upstream in tidal estuaries.	Commonly less than 10 ppm in humid regions; tidal streams contain increasing amounts of chloride (as much as 19,000 ppm) as the bay or ocean is approached. About 19,300 ppm in sea water, and as much as 200,000 ppm in some brines.	Chloride in excess of 100 ppm imparts a salty taste. Concentrations greatly in excess of 100 ppm may cause physiological damage. Food processing industries-textile processing, paper manufacturing, and synthetic rubber manufacturing-desire less than 100 ppm.
Flouride (F)	Amphiboles (hornblende), apatite, fluorite, mica.	Concentrations generally do not exceed 10 ppm in ground water or 1.0 ppm in surface water. Concentrations may be as much as 1,600 ppm in brines.	Flouride concentration between 0.6 and 1.7 ppm in drinking water has a beneficial effect on the structure and resistance to decay of children's teeth. Fluoride in excess of 1.5 ppm in some areas causes "mottled enamel" in children's teeth. Flouride in excess of 6.0 ppm causes pronounced mottling and disfiguration of teeth.

(cont'd)

TABLE B-2 (continued)

Constituent	Major Sources	Concentration in Natural Water	Effect on usability of water
Nitrate (NO ₃)	Atmosphere; legumes, plant debris, animal excrement, nitrogenous fertilizer in soil and sewage.	In surface water not subjected to pollution, concentration of nitrate may be as much as 5.0 ppm but is commonly less than 1.0 ppm. In ground water the concentration of nitrate may be as much as 1,000 ppm.	Water containing large amount of nitrate (more than 100 ppm) is bitter tasting and may cause physiological distress. Water from shallow wells containing more than 45 ppm has been reported to cause methemoglobinemia in infants. Small amounts of nitrate help reduce cracking of high pressure boiler steel.
Dissolved solids	The mineral constituents dissolved in water constitute the dissolved solids.	Surface water commonly contains less than 3,000 ppm; streams draining salt beds in arid regions may contain in excess of 15,000 ppm; some brines contain as much as 300,000 ppm.	More than 500 ppm is undesirable for drinking and many industrial uses. Less than 300 ppm is desirable for dyeing of textiles and the manufacture of plastics, pulp paper, rayon. Dissolved solids cause foaming in steam boilers; the maximum permissible content decreases with increases in operating pressure.

TABLE B-3. DRINKING WATER STANDARDS OF THE
U.S. PUBLIC HEALTH SERVICE
(Ref.60), General Constituents

Substance	Recommended limits of concentrations in mg/l	Mandatory limits on concentrations in mg/l
Alkyl benzene sulfonate (ABS)	0.5	-
Arsenic (As)	0.01	0.05
Barium (Ba)	-	1.0
Cadmium (Cd)	-	0.01
Carbon chloroform extract (CCE)	0.2	-
Chloride (Cl)	250	-
Chromium (hexavalent) (Cr+ ⁶)	-	0.05
Copper (Cu)	1.0	-
Cyanide (CN)	0.01	0.2
Fluoride (F)	†	†
Iron (Fe)	0.3	-
Lead (Pb)	-	0.05
Manganese (Mn)	0.05	-
Nitrate (NO ₃) *	45	-
Phenols	0.001	-
Selenium (Se)	-	0.01
Silver (Ag)	-	0.05
Sulfate (SO ₄)	250	-
Total dissolved solids (TDS)	500	-
Zinc (Zn)	5	-

*In areas in which the nitrate content of water is known to be in excess of the listed concentration, the public should be warned of the potential dangers of using the water for infant feeding.

*See Table B-4.

TABLE B-4. DRINKING WATER STANDARDS OF THE
U.S. PUBLIC HEALTH SERVICE
(Ref.60), Fluoride

Annual average of maximum daily air temperatures, °Fahrenheit	Recommended control limits (fluoride concentrations) mg/l		
	Lower	Optimum	Upper
50.0-53.7	0.9	1.2	1.7
53.8-58.3	0.8	1.1	1.5
58.4-63.8	0.8	1.0	1.3
63.9-70.6	0.7	0.9	1.2
70.7-79.2	0.7	0.8	1.0
79.3-90.5	0.6	0.7	0.8

TABLE B-5. DRINKING WATER STANDARDS OF THE
U.S. PUBLIC HEALTH SERVICE
(Ref.60), Radioactivity

Source	Recommended limits, micromicrocuries per liter
Radium - 226	3
Strontium - 90	10
Gross beta activity	1,000

TABLE B-6. STANDARDS FOR RAW WATER USED AS SOURCES
OF DOMESTIC WATER SUPPLY*

Constituent	Excellent source of water supply, requiring disin- fection only, as treatment.	Good source of water sup- ply requir- ing usual treatment such as fil- tration and disinfection.	Poor source of water sup- ply, requir- ing special or auxiliary treatment and disinfection.
B.O.D. (5-day) ppm			
Monthly average	0.75	1.5-2.5	2.0-5.5
Maximum day or sample	1.0	3.0-3.5	4.0-7.5
Coliform MPN per 100 ml.			
Monthly average	50-100	240-5,000	10,000-20,000
Maximum day or sample	-	<20%> 5,000 < 5%> 20,000	
Dissolved oxygen			
ppm. average	4.0-7.5	2.5-7.0	2.5-6.5
% saturation	50-75	25-75	-
pH.....average	6.0-8.5	5.0-9.0	3.8-10.5
Chlorides, max...ppm.	50	250	500
Iron/Manganese..Max.ppm.	0.3	1.0	15
Fluorides....ppm.	1.0	1.0	1.0
Phenolic compounds			
Max.ppm.	none	.005	.025
Color....ppm	0-20	20-70	150
Turbidity...ppm	0-10	40-250	-

*Source: Reference 60.

TABLE B-7. DRINKING WATER STANDARDS OF THE
WORLD HEALTH ORGANIZATION

Chemical Constituent	Concentrations (mg/l)				
	WHO International (1968)			WHO European (1961)	
	Permissible limit	Excessive limit	Maximum allowable	Recommended limit	Tolerance limit
Ammonia (NH ₄)	-	-	-	0.5	-
Arsenic	-	-	0.2	-	0.2
Cadmium	-	-	-	-	0.05
Calcium	75	200	-	-	-
Chloride	200	600	-	350	-
Chromium (hexavalent)	-	-	0.05	-	-
Copper	1.0	1.5	-	3.0	-
Cyanide	-	-	0.01	-	0.01
Fluoride	-	-	-	1.5	-
Iron	0.3	1.0	-	0.1	-
Lead	-	-	0.1	-	0.1
Magnesium	50	150	-	125	-

APPENDIX C
GUIDELINES FOR PROCESS, DESIGN AND CONSTRUCTION,
AND OPERATION OF SLURRY PIPELINES*

I. PROCESS

A. HYDRAULICS

1. Selection of Carrying Fluid

Engineer: Makes balance among quality, availability, location, cost and environmental impact. Consider wastewater as carrier.

Operator: Must monitor quality and quantity of fluid

Potential Problems: Availability may decrease over project life. Export of water politically sensitive.

2. Selection of Optimum Size Range

Engineer: Specifies positive top size control such as safety screens based on laboratory analysis of material.

Operator: Must strictly enforce top size criteria. Process must be kept in tune. Safety screens must be used and checked for wear.

Potential Problems: Oversize particles can cause blockage of line and excessive wear.

3. Selection of Optimum Concentration and Pipe Diameter:

Engineer: Makes economic balance between diameter and concentration based on specific slurry rheology.

Operator: Must adhere to minimum and maximum concentration limits.

Potential Problems: Possibility of laminar flow if slurry too thin; probably excessive pressure drop if slurry is too thick.

4. Calculation of Pressure Loss

Engineer: Utilizes laboratory data on range of slurry

*Reprinted with permission from Thompson, T.L. and T.C. Aude. Slurry Pipeline Design and Operation Pitfalls to Avoid. Joint Petroleum-Mechanical Engineering and Pressure Vessels and Piping Conf. Mexico City, Mex., Sept. 19-24, 1976. Reference 93.

characteristics plus commercial data; uses tested hydraulic model capacity.

Operator: ---

Potential Problems: Wrong pressure (friction) loss can either add to cost of system unnecessarily or reduce system capacity.

5. Determination of Minimum Operating Velocity

Engineer: Specifies minimum velocity which provides margin of safety above deposition or transition velocity.

Operator: Must strictly enforce minimum operating velocity.

Potential Problems: Operating below minimum velocity for extended periods can cause blockage of line.

6. Determination of Operating Factor

Engineer: Include allowance for downtime, variation in slurry characteristics and reliability of power supply.

Operator: ---

Potential Problems: Improper operating factor in design can result in inadequate throughput capacity.

7. Determination of Surge Pressures

Engineer: Must conduct detailed surge study.

Operator: Must adhere to valve closure times, relief settings, etc.

Potential Problems: Possibility of overpressuring and rupturing line.

8. Consider Bypass Capabilities

Engineer: Performs hydraulic and economic analysis of bypassing alternate pump stations for reduced throughput capacities.

Operator: Adopts procedure for station bypass in emergency situations.

Potential Problems: Bypass velocity criteria must be adhered to or line could be over-pressured.

B. CORROSION-EROSION

1. Establish Design Life

Engineer: Sets design life considering both contractual life and probable operating life.

Operator: ---

Potential Problems: Later conditions may indicate desirability of extending life and pipe wall thickness could be inadequate.

2. Establish Corrosivity of Water and Slurry

Engineer: Performs extensive laboratory tests on full range of slurry variations expected.

Operator: Monitors corrosion rate regularly; runs laboratory corrosivity tests; monitors pH and oxygen levels.

Potential Problems: Corrosivity of water or slurry can cause irreversible damage to pipeline.

3. Select Slurry and Water Inhibitors

Engineer: Evaluates various inhibition methods considering cost, environment and effectiveness.

Operator: Strictly enforces inhibitor dosage criteria and monitors effectiveness.

Potential Problems: Inhibitors must not interfere with slurry dewatering and end use of solids.

4. Minimize Oxygen Presence

Engineer: Designs system for minimum exposure of slurry to oxygen.

Operator: Regularly inspects system for possible ingestion of oxygen.

Potential Problems: Oxygen can radically increase corrosion rate.

5. Determine Metal Allowance

Engineer: Makes economic balance between inhibitor and wall thickness additions.

Operator: Sets up & enforces regular corrosion spool weight measuring program-uses ultrasonics as an interim check.

Potential Problems: ---

6. Reduce or Avoid Slack Flow

Engineer: Conducts a computer analysis to determine all slack flow areas especially during batching. Avoid slack flow by reducing diameter, changing route or installing choke stations. If some slack flow accepted, must provide for replacement or lining.

Operator: Maintains chokes religiously, if installed. Monitors wall thickness regularly in potential slack flow areas.

Potential Problems: Undetected slack flow and resulting cavitation can destroy the pipe wall in a matter of months.

C. OPERABILITY-STABILITY

1. Establish Desired Shutdown/Start-up Capabilities

Engineer: Analyzes slurry in laboratory and makes modifications as necessary to provide "soft" settling slurry. Designs for start-up pressures.

Operator: Follows shut-down, start-up procedures.

Potential Problems: Deviation from start-up and shut-down procedures could cause blockage.

2. Select Maximum Pipeline Slope

Engineer: Based on laboratory tests and operating experience sets maximum slope criteria. Makes trade-off between cost of cuts for slope limitation and potential risk with higher slopes.

Operator: ---

Potential Problems: Excessive slopes could cause settlement to low point during shut-down with possible formation of a blockage.

D. ATTRITION OF SOLIDS

1. In Pipeline

Engineer: Selects particle size, concentration, and operating velocity to avoid excessive heterogeneity.

Operator: Adheres to concentration, size distribution and velocity restrictions.

Potential Problems: Finer material is more difficult to dewater & may have higher pressure drop (No attrition observed, however, in properly designed systems.)

2. In Pumps

Engineer: Sets particle top size compatible with pump valve clearances.

Operator: Minimizes recirculation of slurry through centrifugal pumps.

Potential Problems: ---

II. DESIGN/CONSTRUCTION

A. PUMP STATIONS

1. Number and Location of Stations

Engineer: Makes economic trade-off; diameter and number

of stations; considers infrastructure.
Operator: Maintains accessibility to remote stations; monitors power reliability.
Potential Problems: Additional remote stations give operating complexity; plunger flush water can cause excessive dilution with multiple stations.

2. Pump Type Selection

Engineer: Based on volume, pressure and abrasivity of material selects piston, plunger or centrifugal pumps.
Operator: Monitors pump parts life & establishes a routine changeout schedule.
Potential Problems: Unexpected pump failures can shut-down the system incurring lost production.

3. Number of Pumps per Station

Engineer: Minimizes number of pumps but includes adequate spare capacity.
Operator: Schedules routine maintenance on spare pump unit.
Potential Problems: Adequate sparing is important to maintain high system reliability.

4. Driver Selection:

Engineer: Selects electric motor, diesel engine or other considering cost, availability of fuel and reliability.
Operator: --
Potential Problems: Poor selection of driver type can have deleterious effect on system reliability.

5. Speed Control Selection:

Engineer: Selects speed control based on expected throughput variations as well as start-up procedure. Sizes heat exchanger for maximum slip.
Operator: Follows speed versus time plan for start-up; operates near minimum power consumption level.
Potential Problems: Improper speed control can raise operating costs and make throughput adjustments difficult.

6. Pulsation Dampening

Engineer: Properly sizes and locates pressure dampeners.

Operator: Monitors vibrations and pulsations with pressure transducers.

Potential Problems: Improper dampening can cause reduction in system capability or inoperability.

7. Pump Station Piping and Elbows

Engineer: Uses long radius elbows; avoids dead legs, respects velocity limits in piping.

Operator: Monitors elbows and other potential high wear areas.

Potential Problems: Dead legs can cause sanding; short radius elbows will wear through.

8. Valves

Engineer: Uses Hard-facing in high pressure service; avoids pockets where slurry can pack; considers velocity.

Operator: Lubricates regularly as required.

Potential Problems: Valve wear or packing of solids in cavities can result from poor valve selection.

B. AUTOMATION CONTROL

1. Degree of Automation

Engineer: Designs sophistication compatible with available technicians and needs of system.

Operator: is trained in use of all facets of automated operation.

Potential Problems: Too complex a system can add operating and staffing problems.

2. Synchronization of Operation of Positive Displacement Pumps

Engineer: Selects method of synchronization such as speed control based on suction pressure.

Operator: Monitors set-points.

Potential Problems: Erratic operation & pressure waves, could result from improper synchronization.

C. PIPELINE

1. Degree of Tapering

Engineer: Tapers pipeline considering surge pressures, static shut-off, head, corrosion allowance and installation.

Operator: ---

Potential Problems: Excessive tapering can cause over-pressure problems as well as confusion in construction.

2. Above Ground vs Buried

Engineer: Makes economic and environmental trade-off of above ground vs. buried; considers thermal expansion, susceptibility to freezing, pipe supports.

Operator: Maintains cathodic protection, coatings and other protection.

Potential Problems: ---

3. Freezing Protection

Engineer: Considers burial below frost line, insulation heat tracing and special operating techniques.

Operator: Maintains continuous monitoring of slurry temperature; utilizes special operating techniques; avoids shut-downs.

Potential Problems: Partially frozen line could rupture or cause blockage.

4. Welding Standards

Engineer: Establishes welding standard for slurry pipeline.

Operator: ---

Potential Problems: Excess weld metal penetration can cause erosion through secondary turbulence.

5. External Corrosion

Engineer: Provides appropriate coating system, tests leads and temporary protection.

Operator: Obtains corrosion survey after line has "settled-in"; Installs required cathodic protection.

Potential Problems: Corrosion damage can occur very rapidly in "hot spots".

D. TANKAGE

1. Sizing

Engineer: Selects size and number of tanks for cost, flexibility and reliability.

Operator: ---

Potential Problems: ---

2. Agitators

Engineer: Sizes to avoid solids deposits; reversing types preferred.

Operator: Checks agitator for continuous operation; watches for sanding, excessive vibration.

3. Special Tank Design

Engineer: Requires extra steel for maximum specific gravity of slurry, access for cleaning required; plans for desanding needed.

Operator: Maintains concentration below maximum; practices desanding tank.

Potential Problems: ---

III. OPERATION

A. SELECT MODE OF OPERATION

Engineer: Prepares detailed operating procedure; simulate by computer if necessary.

Operator: Trains operators and follows prescribed operating procedure.

Potential Problems: Virtually all blockage and erosion and corrosion "problems" are caused by operator error either by improper monitoring for early warning, or faulty procedures.

B. EMERGENCY TECHNIQUES

Engineer: Provides emergency procedures including plug location and unplugging procedure.

Operator: Drills operators in emergency techniques and procedures.

Potential Problems: Virtually all blockage and erosion and corrosion "problems" are caused by operator error either by improper monitoring for early warning, or faulty procedures.

C. STAFFING

Engineer: Prescribes staffing based on local availability and system design.

Operator: Staffs and trains; operators should be on site during initial start-up.

Potential Problems: Virtually all blockage and erosion and corrosion "problems" are caused by operator error either by improper monitoring for early warning, or faulty procedures.